EVALUATION OF EMULSION BASED WARM MIXES FOR PAVING APPLICATIONS

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Under the guidance of

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CERTIFICATE

This is to certify that the Project Report entitled "**EVALUATION OF EMULSION BASED WARM MIXES FOR PAVING APPLICATIONS**" submitted by **Mr. Madan Mohan Padhi bearing Roll No. 611CE302** in partial fulfillment of the requirements for the award of **Master of Technology (Research)** Degree in Civil Engineering at National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in this Project Report has not been submitted to any other University/Institute for the award of any Degree or Diploma.

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ABSTRACT

Due to increase in energy costs and emission problems in hot mix asphalt, it brought a great interest to the researchers to develop the warm mix technology for pavement constructions. It is a typical method in the bituminous paving technology, which allows production and placement of bituminous mixes at lesser temperatures than that of hot mix asphalt (HMA), which involves an environmental friendly production process that involves the use of organic additives, chemical additives and water based technologies. In this study an attempt has been made to prepare warm mixes by first pre-coating the stone chips with medium setting bitumen emulsion (MS) and then mixing coated aggregates with VG 30 bitumen at a lower temperature than normally required. These two binders have been taken in equal proportions to form the binder. Three mixing temperatures were maintained, namely temperatures 110°C, 120°C and 130°C. Marshall Samples have been prepared using this methodology with dense bituminous macadam (DBM) and bituminous concrete (BC) gradings as per the specifications of MORTH and subsequently Marshall Properties were studied with the main objective of deciding the type of filler, setting time of emulsion, optimum temperature of mix preparation and optimum bitumen-emulsion composition forming the binder. In this study it has been observed that out of three mixing temperatures tried, the mixes prepared at 120^0C with bitumen-emulsion composition 80:20 for DBM warm mix and 70:30 for BC warm mix offer highest Marshall Stability and highest indirect tensile strength (ITS), while satisfying other Marshall parameters. It is also seen that the optimum binder contents for warm mixes are 5.1% with 80:20 bitumen emulsion composition for DBM warm mix and 4.9% binder with 70:30 bitumen emulsion composition for BC warm mix, each prepared at 120°C. The tensile strength ratio and retained stability parameters are also found to be reasonably satisfactory in such warm mixes, thus prepared. The results of warm mixes are found to be comparable to the HMA.

Key words: Warm Mix Asphalt (WMA), Hot Mix Asphalt (HMA), Medium Setting Emulsion, Marshall Properties, indirect tensile strength, tensile strength ratio, retained stability

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LIST OF ABBREVIATIONS

HMA	Hot mix asphalt
BC	Bituminous concrete
DBM	Dense bound macadam
MORTH	Ministry of Road Transport & Highways
OBC	Optimum Binder Content
WMA	Warm mix asphalt
ITS	Indirect Tensile strength
MS	Medium Setting Emulsion
TSR	Tensile Strength Test
VFB	Voids filled with bitumen
VMA	Voids with mineral aggregate
VA	Air voids

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Warm Mix Asphalt (WMA) is a fast emerging technology, now accepted worldwide. The idea of use of lower temperatures to produce asphalt mixes is not new.WMA is defined as the asphalt mixture whose mixing temperature is from 100°C to 135°C (Hurley and Prowell,2005). In this technology organic additives, chemical additives and foaming technology are used to manufacture and spread asphalt mixes at lower temperature than conventional Hot Mix Asphalt (HMA) by decreasing the asphalt viscosity.WMA is produced, placed and compacted at temperature10°C to 40°C lower than the conventional Hot Mix Asphalt (D' Angelo et.al, 2008). It is a technology that allows lowering of the production and paving temperature of Hot Mix Asphalt (HMA) by reducing the viscosity of binder which helps in increasing the workability of mixture without compromising the performance of asphalt. It reduces energy consumption, carbon dioxide emission, oxidative hardening of Asphalt, overhead and total costs of the Asphalt industry by lowering the production temperature thereby creating a better working environment. However, the lower mixing temperatures have raised concerns on the performance of the mixtures. So there is need to thoroughly evaluate and characterize the WMA mixtures to ensure adequate performance.

1.2 Potential benefits and drawbacks

Warm Mix Asphalt (WMA) technologies use technological advances that reduce the temperature of compaction and production. There are certain other benefits that are discussed below (Zaumanis, 2010). WMA technologies promise a number of benefits. The specific benefits depend upon which specific WMA technology is used. However, the benefits can be categorized in three groups:

- Environmental: Reduced emissions of CO_2 (carbon dioxide) and other greenhouse gasses because of reduced temperature needed to produce and compact asphalt

- Production
    a) Higher Reclaimed Asphalt Pavement (RAP) percentage in mixes is possible because of decreased viscosity of the stiff binder in RAP.
    b) Less ageing of binder during the production and paving process, thus improving longevity of pavement service life
    c) Easier permit for a plant site in urban areas, because of reduced emissions, dust and noise
- Paving
    a) Improved workability and compaction because of lower bitumen viscosity at paving temperature
    b) Longer haul distances due to possibility to pave at lower temperature
    c) Reduced time of pavement cooling because of lower initial temperature
    d) Less inconvenience to public near production and work sites as emissions of fume and odour are reduced.

1.3 Benefits of warm mix as compared to hot mix

As per Button (2007) and Zaumanis (2010) WMA offers some benefits as compared to Hot Mix Asphalt as mentioned below.

- It requires lower production and placement temperatures thereby reducing energy costs.
- Less aging of binder during plant mixing and placement, thus improving longevity of pavement service life.
- Warm mix reduces thermal segregation and emissions from mixing plants and during placement hence decreases the dust production.
- extended paving season (i.e., paving during cooler weather)

- Due to less difference between ambient temperature and mix temperature, it provides expanded market areas and decreased mobilization cost.
- It requires less paving in non-attainment areas.
- It requires less wear on asphalt plant due to reduced temperature.
- Reduces time of pavement cooling because of lower initial temperature.

1.4 Benefits of warm mix as compared to cold mix

As per Soto and Blanco (2004) and Els (2004) the following are the advantages of Warm mix over Cold mix.

- requires essentially no curing time before trafficking
- allows use of higher quality aggregates that cannot be used in cold mixes
- provides better quality mixes due to the total coating of aggregates and binder
- improves handling and compaction over cold mix

1.5 Concerns about warm mix

There are some concerns about the performance and implementation of WMA. These are listed below according to **(**Zaumanis, 2010).

❖ Rutting

Due to decrease in ageing at lower production temperatures and increased moisture content for foaming technologies premature rutting is seen in WMA.

❖ Low Temperature Behaviour

The low temperature properties of bitumen used in organic WMA technologies can be slightly different than expected from conventional HMA. This change in performance can be explained through the crystallisation of waxes that tend to increase the viscosity and stiffness of the binder. Therefore low temperature binder properties should be evaluated to predict the possible changes of bitumen in WMA.

- Economical

There are some concerns about the implementation of WMA production technology because of its cost. It is necessary to prove the potency of WMA over HMA so that the use of this technology becomes widespread.

- Water Presence

Foaming and some of the chemical WMA technologies are somewhat connected with the introduction of water in the initial mixing process. Because of possible incomplete vaporization of water during the mixing and laying process residual water in the mixtures may cause problems of premature rutting and stripping of pavements.

In India majority of road network is comprises of bituminous pavement in which Hot Mix Asphalt (HMA) is used predominantly as a paving mix. Indian rural road network is developing continuously at a faster rate. Hence the paving mix like Warm Mix Asphalt (WMA) should be tried as it reduces the problems associated with HMA. Considering the concerns involving use of WMA as mentioned above, it was found necessary to evolve a procedure to develop a WMA mix in simple way of adding and partially pre coating dense graded aggregates with medium setting emulsion (MS) and then using those with fresh bitumen at a lower temperature than normal HMA. The paving mixes developed have thus been evaluated in terms of certain engineering parameters. The effects of temperature and emulsion concentrations in binder have been studied with respect to Marshall Properties in the mixes. The performances of warm mixes with respect to tensile strength and moisture susceptibility are also studied.

1.6 Objectives of the present study

The main objectives of the present study are:

- To develop a procedure for warm mix asphalt using medium setting emulsion (MS).

- To investigate and study the effects of varying temperatures on mix preparation and emulsion concentration in terms of Marshall Properties for both the types of mixes (BC and DBM mixes).
- To decide the best mix parameters such as temperature for the preparation of warm mix, emulsion concentration in binder and optimum binder content.
- To study the effects of Indirect Tensile Strength Test (ITS) of warm mixes at different temperatures.
- To study the moisture susceptibility characteristics of mixtures in terms of their tensile strength ratio and retained stability values.

1.7 Organization of thesis

The whole thesis is divided in to six chapters and organized in following manner.

i. Chapter 1. Introduction: Gives a brief idea about the warm mix asphalt and its advantages compare to other bituminous mix like cold mix and hot mix.

ii. Chapter 2. Review of literature: Works carried out on warm mix till date has been discussed in this chapter and made a motivation to research on WMA.

iii. Chapter 3. Experimental investigation: In this chapter the methodology which is used for preparation of WMA samples and materials used for preparation have been discussed.

iv. Chapter 4. Experimental results and discussions: In this part, the results obtained from experimental work in laboratory have been discussed.

v. Chapter 5. Conclusions: This is the last chapter of the thesis and the conclusions observed from the experimental have been summarized.

CHAPTER 2

REVIEW OF LITERATURE

2.1 Introduction

Warm Mix Asphalt (WMA) developed in Europe in the mid 1990's. This technology is known as warm asphalt mixes in areas throughout Europe, generally been referred as Warm Mix Asphalt in the United States. Warm Mix Asphalt has not only been successful in its intended purpose of lowering asphalt fumes and emissions through lowering mixing and compaction temperatures, but has also been found to possess numerous other benefits for the asphalt paving industry. Warm Mix Asphalt may also act as a compaction aid for stiffer mixes that are more difficult to compact, such as Stone Matrix Asphalt, when used at typical compaction temperatures. Enormous research and development have been done on warm mix asphalt by number of researchers. After review of literatures on the subjects some of the important research contributions are presented below. The Review of literature is divided into two parts. The first part gives detail idea about the various technologies involved in the formation of WMA along with the contribution of various researchers under that particular technology who have used wide varieties of additives for making warm mixes, which is sub categorized into three parts basing on organic additive, chemical additive, and foaming technology. Finally, the second part consists of various literatures on mix design process of warm mixes.

2.2 WMA technologies

There are different technologies and different additives used for the production of Warm Mix Asphalt (WMA). Warm-mix technology uses various techniques to reduce effective viscosity of the binder by enabling full coating and subsequent compact-ability at lower temperatures. These similarities have given rise to classifications as described below:

- Based on Degree of Temperature reduction
- Based on the Technologies used

2.2.1 Based on degree of temperature reduction

One way of classifying the WMA technologies is by degree of temperature reduction. Below diagram shows the classification of various application temperatures for asphaltic concrete, ranging from cold mix to hot mix. Warm mix asphalt mixes get separated from half-warm asphalt mixtures by the resulting mix temperature.

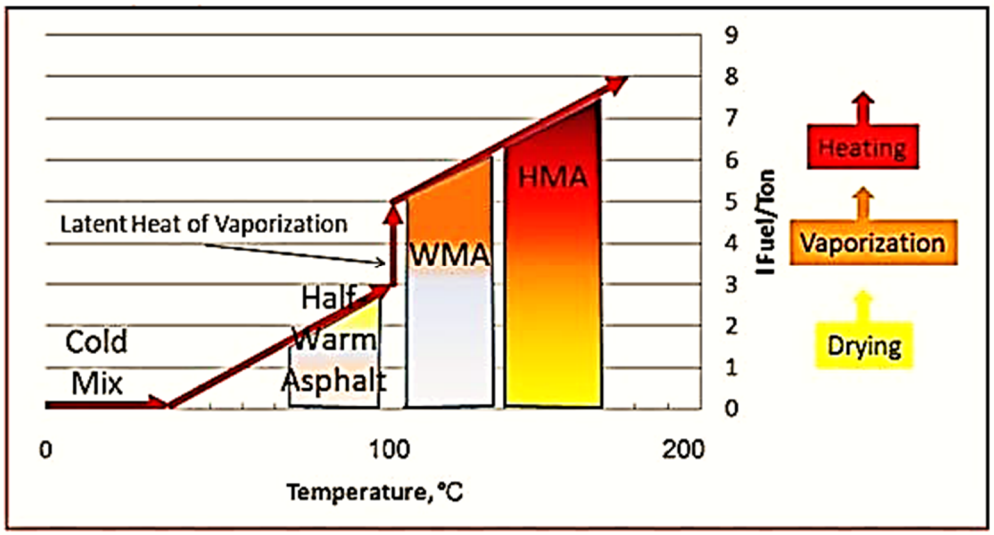

Fig 2.1 Classification by temperature range (D' Angelo et.al, 2008)

Asphalt mixtures according to their mixing temperature and energy consumed for heating process of materials are divided into four parts (D' Angelo et.al, 2008):

- **C**old Mix Asphalt (CMA) - Asphalt Mixture are produced using Emulsion, Aggregate, Filler at temperature between 10°C to 30°C. It is environment friendly and eco-friendly as it eliminates heating of aggregates.
- Half Warm Mix Asphalt (HWMA) – Asphalt Mixture produced at temperature below water vaporization i.e. 65°C to 100°C.
- Warm Mix Asphalt (WMA) – Asphalt mixture produced at temperature range of 110°C to 130°C. WMA is a modified hot mix asphalt mixture which is produced,

placed and compacted at a temperature 10^{o}C to 40^{o}C lower than the conventional hot mix asphalt mixture.

- Hot Mix Asphalt (HMA) – Asphalt mixture produced at temperature between 150°C to 180°C. The aggregates, binders are heated at high temperature.

2.2.2 Based on the technologies used

Another way of classifying WMA is basing on the technologies used. This most widely used classification gives three categories (Zaumanis, 2010, Erik Olesen, Erik Nielsen)

(i) Foaming processes (divided into water-containing and water-based processes)

(ii) Addition of organic additives

(iii) Addition of chemical additives

2.2.2.1 Foaming Technologies

Foaming technologies use small amount of cold water injected into the hot binder or directly in the asphalt-mixing chamber (Larsen, 2001). The water rapidly evaporates and encapsulates in the binder, producing large volume of foam. The foaming action in the binder increases the volume of binder and lowers the viscosity, which improves coating and workability of binder. In the foaming processes, enough water is added to cause foaming without creating stripping problems. To ensure this, some of the producers advise to use anti-stripping agents so that moisture susceptibility of an asphalt mixture is minimized. The foaming technologies can be

(a) Water based (direct method technologies) and

(b) Water containing (indirect method technologies).

(a) Water- based Technologies (direct method)

Technologies such as Double Barrel Green, Ultra foam GX, Low Energy Asphalt use foaming process which is created by directly injecting water into hot binder flow using special equipment or technology (since each company makes its own equipment). The water rapidly evaporates, producing a large volume of foam, which slowly collapses. This category divided into the types of product used to make the mix (Zaumanis, 2010).

(i) Double Barrel Green, Aqua black WMA, Warm Mix Asphalt System

These WMA processes use some type of nozzle to inject water into asphalt binder stream. Each technology uses equipment developed by the individual company. The nozzles are computer controlled to adjust the foaming rate. Small amount of water is added to foam the binder. The water creates steam which encapsulate the binder resulting in foaming and large volume increase of the binder, which decreases the viscosity thus allowing aggregates to be coated at lower temperatures.

(ii) Low Energy Asphalt (LEA)

Low Energy Asphalt (LEA) is a foaming process in which hot asphalt is first mixed with heated coarse aggregate only. Once all coarse aggregates are coated a fine aggregate or RAP (Carter et al. 2010) is mixed with added water and added to the asphalt coarse aggregate mix. The moisture in the fine aggregates or RAP causes the asphalt binder to foam (Button et al. 2007). The originality of the process lies in the best use of changes in the condition of the bitumen, fluid when it is hot and the ability to transform into foam or emulsion when in contact with water (Romier et al., 2006).

(iii) Wam – Foam

The process consists of a soft binder that is first mixed with the aggregate until it is fully coated. Cold water is then added to the harder binder at a rate of 2 to 5 percent by mass of

hard binder (D'Angelo et al. 2008) to cause a foaming action and the foamed binder is added to the soft binder mixture (Button et al. 2007). The soft and hard binder blend is selected to produce the required final binder grade (Middleton and Forfylow 2009). The hard binder is typically around a 58/64-22 grade (D'Angelo et al. 2008). The process creates a mix that has acceptable workability at lower production temperatures. The process may be difficult to perform effectively in the laboratory setting, (Wasiudden et al. 2007).

(a) Water -containing Technologies (indirect method):

(i) Aspha-Min, Advera

These technologies use synthetic zeolite to produce the foaming process. The product is composed of alumina silicates of alkali metals and is hydro-thermally crystallized. The crystallization has approximately 20% water, which gets released from the zeolite structure as the temperature rises. This causes a micro foaming effect in the asphalt mix, which lasts about 6-7 hours (Chowdhury and Button, 2008; D'Angelo et al., 2008). The structure of the zeolites has large air voids where cations and even molecules or cation groups (such as water) can be contained. Their ability to lose and absorb water without damaging the crystalline structure is the main characteristic of this silicate framework (Chowdhury and Button, 2008). At high temperatures between 100°C and 200°C the Zeolite releases small amounts of water, creating a controlled foaming effect that leads to a slight increase in binder volume and reduces the viscosity of the binder.

(ii) Evaluation of foaming technology for use in warm-mix asphalt

Maccarone et al. (1994) Studied about Warm-Mixed asphalt-based foamed bitumen with very high binder content emulsions and concluded that the use of mixes for use on roads was gaining acceptance worldwide due to energy efficiency and lower emissions.

Jenkins et al. (1999) introduced a new process involving half-warm foamed bitumen. He explored the concepts and possible benefits of heating wide variety of aggregates to temperatures below 212°F before the application of foamed bitumen. Preheating aggregates enhanced particle coating, mix cohesion, tensile strength, and compaction. This is particularly beneficial for mixes containing reclaimed asphalt pavement (RAP) or densely graded crushed aggregates.

Harrison and Christodulaki, (2000) observed that by adding Aspha-min to the mix at the same time as the binder, a very fine water vapour is created. This release of water creates a volume expansion of the binder that results in the formation of asphalt foam, allowing increased workability and aggregate coating at lower temperatures.

Koenders (2002) introduced foamed WMA technologies to produce asphalt mixtures at lower temperatures.

Hurley and Prowell (2005) stated that the addition of Aspha-min lowered the air voids measured in the gyratory compactor. It improves the compaction ability of both the superpose and vibratory compactor. Statistical analysis of test results indicated an average reduction in air voids of 0.65% using the vibratory compactor.

Goh et al. (2007) evaluated the performance of wma after the addition of Aspha- min, based on the MEPDG. The predicted rut depths from the MEPDG simulations demonstrated that WMA could decrease rutting, and the greatest difference of rutting between wma and its control HMA could be up to 44%.

Lee et al. (2007) prepared three types of CIR-foam specimens: CIR-foam with 1.5% of Sasobit®, CIR-foam with 0.3% Aspha-min®, and CIR-foam without any additive. They reported that wma additives have improved the compaction ability of CIR-foam mixtures resulting in a lower air void. The indirect tensile strength of CIR-foam mixtures with

Sasobit® was the highest and the dynamic moduli of CIR-foam mixture with wma additives were higher than one without any additive. Flow number of CIR-foam mixtures with Sasobit® was the highest followed by one with Aspha-min® and the specimens without additive.

Goh SW and You Z (2008) stated that warm mix asphalt made with 0.5% Aspha-min and compacted at 120°C shows a higher performance for dynamic modulus when the mixture was compacted at 100°C hence indicate that stiffness is lost when the mixing temperature is reduced for HMA, but this loss can be minimised by using WMA and HWMA systems.

Wielinski et al. (2009) conducted a study based on laboratory tests and field evaluations of foamed wma projects and concluded that the Hveem and Marshall properties of HMA and wma were similar, and fulfil the Hveem design and the mixture property requirements.

Hodo et al. (2009) stated that the foamed asphalt mixtures presented good workability at lower temperatures, and implied greater ease in placing and compacting the mixtures. He suggested that on adding anti- stripping agents to the mixture, the moisture damage resistance would be improved.

Middleton and Forfylow (2009) found that Sasobit®, Evotherm®, Aspha-min®, LEA, Double Barrel® Green and WAM-Foam® all had viscosities that were adequate enough to compact at temperatures that were lower than that of traditional HMA. Hence he concluded that WMA additives help improve the viscosity and workability of asphalt at decreased temperatures.

Xiao et al, (2009) used virgin binder (PG 64-22), Crumb Rubber Modified (CRM) binder (PG 64-22 + 10% 40 mesh rubber) and two aggregate sources (A and B), two additives namely Asphamin and Sasobit were used for the preparation of WMA mixes. He observed that the fatigue life of the mixtures made with crumb rubber and WMA additive is greater

than the control mixtures with no (rubber and WMA additive), except the mixtures containing Asphamin additive. He reported that TSR values of WMA mixtures with Sasobit® and Aspha-min® additives were lower than 85% but increased above 85% when 1.0% of hydrated lime was added**.**

National Cooperative Highway Research Program (NCHRP) (2009) performed various research studies involving the WMA technologies such as Evotherm, Sasobit, Advera, LEA, Gencor foaming etc. The research indicated similar volumetric properties for the WMA and HMA mixtures and differences in the moisture sensitivity between both the mixtures, but also showed improved resistance to moisture damage with addition of anti-strip additives.

2.2.2.2 Organic additives

Organic or wax additives (such as Sasobit, TLA-X Warm Mix etc.) are added to asphalt mix or blended with bitumen to achieve the temperature reduction by reducing viscosity of binder above the melting point of the waxes. The type of waxes is carefully selected so that the melting point of the wax is higher and minimizes embrittlement of the asphalt at low temperatures. Since the binder is at a higher temperature hence the process is maintained through the mixing and compaction procedures. This type of additive is formed by a long chain of hydrocarbons atoms which is sold at room temperature and has melting point around 100°C. Most common commercial products of organic additives with their description are explained below.

Sasobit

Sasobit® is a wax made through Fischer-Tropsch synthesis (D'Angelo et al. 2008) by the Sasol Wax Corporation that allows the wax to have hydrocarbon chains of around 100 carbon atoms (Hurley and Prowell 2005). It is a long-chain aliphatic hydrocarbon wax with a melting range between 85°C and 115°C, high viscosity at lower temperatures, and low viscosity at

higher temperatures. This allows Sasobit® to be fully soluble in asphalt above 115°C (Kanitpong et al. 2007). Sasobit® is also able to increase the resistance to permanent deformation of the asphalt when it is cooled below its melting point by forming a lattice structure in the asphalt (Kanitpong et al. 2007, Akisetty et al. 2010)

TLA-X Warm Mix

TLA-X Warm Mix is another organic WMA additive. Trinidad Lake Asphalt (TLA) is naturally occurring lake asphalt (Martin et al. 2011). It is mined from a lake deposit in solid form and is composed of mineral matter, soluble bitumen, water and other minor components (Prowell et al. 2009). TLA has a high resistance to cracking and permanent deformation, is easily blended with traditional asphalt binders, maintains a high stability level in asphalt mixtures and provides good adhesion to aggregates when used as an asphalt binder (Prowell et al. 2009).

(i) Evaluation of organic additive for use in warm-mix asphalt

Hurley and Prowell (2005) indicated that when the mixing temperatures are reduced for wma, the mixes show increased tendencies towards rutting and moisture susceptibility. Thus, he concluded that the wma producers should find the right balance between lowering the mixing temperatures by using sufficient amount of anti-stripping agents and drying of the aggregates used in the mixes.

Hurley and Prowell (2006) evaluated the effects of Sasobit on pavement performance .He used two aggregates (limestone and granite) and two binders (PG 64-22 and PG 58-28). The addition of Sasobit lowered the measured air voids in the gyratory compactor and consequently improved the compaction ability of mixtures. Mixture stiffness characteristics represented by a resilient modulus were not affected by the addition of Sasobit PG 64-22.

Lu and Redelius (2006) studied the effect of asphalt that contains wax naturally. They concluded that using waxy bitumen, the asphalt mixtures showed higher fracture temperature with regard to water sensitivity, also found that adding wax to asphalt does not affect the water sensitivity.

Wasiuddin et al. (2007) studied the rutting potential and the rheological properties of the binder. WMA mixtures with Aspha-min and Sasobit additives studied here. A decrease in the rut potential of the mixtures observed with the decrease in the production temperatures.

Goh et al. (2007) evaluated the performance of several WMA mixtures in comparison with HMA mixtures. Aspha-min, Sasobit, Evotherm, Asphaltan B were used as wma additives and their effects were evaluated. Warm mix mixtures had shown lower predicted rut depth than the conventional HMA mixture and dynamic modulus values were not significantly different between the mixtures. Warm mix technologies has shown significant reduction in mixing and compaction temperature.

Goh and You (2008) performed a field study to evaluate the rutting performance of the wma mixture with Sasobit additive in comparison with a control HMA. The warm mix showed similar rutting performance as compared to the control HMA.

Diefenderfer and Hearon (2008) studied Sasobit warm-mix material. The performance of the WMA and HMA sections was similar with respect to moisture susceptibility, rutting, potential, and fatigue resistance.

Mallick et al. (2008) evaluated the effects of Sasobit on asphalt mixtures with a high percentage of RAP material. He concluded that the addition of Sasobit helped to lower the viscosity of the asphalt binder at higher temperatures.

Diefenderfer et al. (2008) evaluated the long-term performance effects of WMA. He evaluated that Sasobit and Evotherm did not have a significant effect on the results of the MEPDG performance predictions when compared to the predictions of conventional HMA mixtures. The performance grading of the recovered binder indicated reduction in the rate of in-service aging of the binder of WMA produced by Sasobit, when compared to control HMA.

Mogawer et al. (2009) evaluated the effects of adding varying dosages of Sasobit on the performance of mixtures containing RAP. He concluded that addition of 1.5% Sasobit changed the PG grade of the base binder from PG 64-28 to PG 70-22, and addition of 3.0% Sasobit changed the binder grade to PG 70-16.

Russell M et al. (2009) conducted an experimental field study involving a control HMA mixture and a wma mixture with Sasobit additive. Sasobit showed no effect on the resilient modulus of the asphalt mixtures. The resulting mixtures however showed poor resistance to moisture damage as measured by the tensile strength ratio (TSR).

Austerman et al. (2009) found that with dosages of 1.5% and 3.0% Sasobit® decreased viscosity and improved workability when compared to the control binder.

Bonaquist, R (2009) indicated similar volumetric properties for the WMA and HMA mixtures. The research showed differences in the moisture sensitivity between HMA and WMA mixtures, but also showed improved resistance to moisture damage with addition of anti-strip additives.

Kridan et al. (2010) developed mix design procedures for warm mix asphalt using Marshall Method. They found that the addition of Sasobit additive in asphaltic mix reduces the air voids content in total compacted mixes. The general trend of increasing Sasobit additive in

mixes on resilient modulus values was similar to the control mix at mixing temperature of 135°C. There were no substantial differences in volumetric properties between the control mix and the Sasobit mix at 135°C.

Xiao et al. (2010) found similar results when Aspha-min®, Sasobit® and Evotherm® were used as WMA additives. The rutting depths for each WMA did not vary significantly when compared to the control HMA. Therefore, the rutting susceptibility of WMA with these additives would be approximately the same as HMA.

2.2.2.3 Chemical additives

Chemical additives such as CECABASE RT®, REDISET WMX etc come under the third type of WMA technology that is commonly used. Usually it includes a combination of emulsification agents, surfactants, polymers, anti-stripping agents and additives to improve coating, improve mixture workability, and compaction.

(i) Cecabase RT®

It is a patented liquid chemical additive that is made of 50% renewable raw materials. Recommended rates of addition range from 0.3 to 0.5 percent by weight of asphalt binder and Cecabase RT® can be introduced directly into the asphalt line in the plant (Prowell et al. 2009). It has been observed that Cecabase RT® acts at the aggregate/binder interphase to improve workability of the mix without changing the rheological properties of the binder (Gonzalez-Leon et al. 2009).

(ii) Rediset WMX

Rediset WMX is a combination of cationic surfactants and organic additive based rheology modifier. By addition of (1.5-2) % by weight of bitumen, it allows reduction of production temperature by 15^{o}C to 30^{o}Ccompared to HMA. It chemically modifies the bitumen and encourages active adhesion that improves the wetting of aggregates by binder. It is produced in a solid additive form and contains surfactants and rheology modifiers (Martin et al. 2011).

Rediset WMX can act as an anti-stripping agent to improve moisture susceptibility and the surfactants contained within it help promote better adhesion of binder to aggregates, even when the aggregates are wet (Prowell et al. 2009)

(iii) Evaluation chemical additive for use in warm-mix asphalt

Takamura et al. (2005) He studied that thin water film between the aggregate and asphalt droplets improve workability of the mix even at temperatures below 90°C. The study divulges that the cationic emulsifiers in the Evotherm emulsion adsorb onto the aggregate surface with their positively charged head groups and expose their hydrocarbon tails outward. This makes the aggregate surface oil-wet, which promotes strong asphalt adhesion for moisture resistant.

Hurley et al. (2005 & 2006) conducted laboratory studies on and Evotherm™. He reported that this technology is capable of reducing the mixing and compaction temperatures of the asphalt mixtures and simultaneously improved the compaction ability of the asphalt mixture and resulted in lower air voids. Evotherm showed increased tendency towards rutting and moisture susceptibility, as the mixing and compaction temperatures were lowered.

NCAT (2005) evaluated the use of Zeolite, Sasobit and Evotherm as potential additives to produce warm asphalt mixtures at temperatures lower than the conventional asphalt mixtures. An infrared camera was used to monitor the thermal consistency during paving. Improved compaction ability was reported at temperatures as low as 190°F. These additives showed no effect on the resilient modulus of the asphalt mixtures. The resulting mixtures however showed poor resistance to moisture damage as measured by the tensile strength ratio (TSR).

Dinis-Almedia, M. (2012) observed that most appropriate design to determine the optimum emulsion content for WMRA is the stiffness test. Lower asphalt emulsion content was the most likely reason for the maximum value. The test method cannot be generalised as the main

test for design of WMA mixes and has suggested that further research was needed for different mix compositions.

2.3 WMA mixture design

One of the main issues is to determine if mixture design for WMA can be performed exactly like HMA. Based on literature, it was found that standard mix design procedures for HMA must be modified to accommodate WMA. Specific elements in the mixture design process are discussed below.

2.3.1 Binder grade selection

Romier et al. (2006) stated that LEA mixes as well as other warm mix products use the same asphalt grades in the same proportions as HMA.

Newcomb (2006) stated that with certain WMA processes, it may be possible or even advisable to use one grade harder asphalt than that normally used with HMA.

Hurley and Prowell (2005a,2005b) observed that Sasobit and Aspha-min mixtures (two mixtures each made using granite and limestone), containing PG 64-22 binder and mixed/compacted at temperatures significantly lower than that of the corresponding control HMA mixtures which contained PG 58-28, had nearly the same air void level. Thus suggested to use asphalt in WMA that is one grade higher than that typically used in HMA.

2.3.2 Selection of optimum binder content

Hurley and Prowell, (2006a) used modified Superpave mixture design procedures including 125 gyrations of the Superpave gyratory compactor and standard HMA mixing and compacting temperatures.

NCAT recommended determining the optimum asphalt content (OAC) without inclusion of the warm mix additive using standard HMA design procedures. This is because the WMA additives enhance compaction so effectively that the OAC is reduced by about one-half a percentage point below that of an equivalent HMA.

Romier et al. (2006) states that laboratory mix design methods for HMA apply for design of WMA paving mixtures. However, laboratory procedures (mixing and compaction) must be adjusted to the temperature of the mixes resulting from the plant mixing process.

Newcomb (2006) suggests that, any modifications to the Superpave mixture technology required for designing WMA, research will be needed to establish.

2.3.3 Aggregate gradation

Hurley and Prowell (2005a, 2005b); Kuennen, (2004); Romier et al., (2006) Stated that warm mix asphalt technology (WMA) uses conventional dense graded mixtures as like we use for hot mix design (HMA).

Maccarone (1994) confirmed that the gradations used in HMA mix design are even used for asphalt mixtures produced at ambient temperature using foamed or emulsified asphalt.

.**Koenders et al. (2000), Romier et al. (2006) ,Larry Michaels (2007)** pointed out that WMA processes should be equally applicable to typical types of asphalt mixtures other than dense-graded mixes (i.e. SMA, open graded, stone filled, coarse base mixtures).

Kristjansdottir (2006) reported that Sasobit has not only been used with dense-graded mixtures in Germany but also in stone mastic asphalt (SMA) and guss asphalt.

Romier et al. (2006) and Jenkins et al. (1999) stated that several WMA processes (e.g., WAM-Foam, LEA) have demonstrated success in mixtures containing recycled asphalt pavement (RAP).

2.3.4 Specimen compaction

Hurley and Prowell, (2005a, 2005b, 2006a, and 2006b) stated that standard HMA laboratory compaction procedures (i.e., 125 gyrations of the Superpave gyratory compactor) have proven to be acceptable for WMA mixtures.

Hurley and Prowell (2006a) demonstrated clearly that Aspha-min, Sasobit, and Evotherm significantly lowered the required compaction temperature to achieve essentially equivalent air voids as a HMA mixture using the same aggregate type and gradation.

2.3.5 Specimen cure time

WMA products that do not depend on moisture to enhance workability and compaction (e.g., Sasobit, Asphaltan B) do not require curing time. However, for those products that incorporate moisture to promote aggregate coating, workability, and compaction (e.g., Evotherm, Aspha-Min, and WAM-Foam), some cure time may be needed to expel the moistures.

2.4 Concluding Remarks

The review of literatures clearly indicates the diversified research works that have been done in warm mix asphalt using different types of additives. The review covers use of additives of various forms, binders of various grades, aggregates of various types and gradations for preparation of warm mixes. It is clearly seen from the literature that the preparation of warm mixes involved broadly the use of bituminous binders in three different procedures i.e. foam technique, use of organic additives and chemical additives all applied to normal bitumen. These procedures and techniques are not only costly but are also difficult to avail in the laboratory. Further, the use of emulsion for preparation of warm mix asphalt is observed to be

scanty. Therefore the preparation of warm mix with emulsion in a specific way being considered to be simple to achieve, is the motivation of present work.

2.5 Scope of work

Based on review of literature the following scopes have been identified for the present study.

a. Selection of all materials used normally used in Indian context, for preparation of warm mixes including aggregate gradings.
b. Conduct of several trials starting with principle of partial coating of aggregates with the help of bitumen emulsion followed by mixing with bitumen at warm temperatures, with the objective of development of a procedure for preparation of warm mixes.
c. Selection of filler type, setting time of emulsion, bitumen-emulsion composition for the preparation of specified warm mixes.
d. Evaluation of warm mixes produced in terms of Marshall Properties with several variables such as temperature of mix preparation and bitumen-emulsion composition.
e. Deciding the best mix parameters such as temperature of mix preparation, emulsion concentration in binder, optimum binder content for the preparation of warm mixes.
f. Evaluation of warm mixes in terms of Marshall Properties, Indirect Tensile Strength and moisture susceptibility characteristics.

CHAPTER 3

EXPERIMENTAL INVESTIGATIONS

3.1 Introduction

In this chapter the different types of materials used and the procedure for preparation of the WMA samples has been described. For preparation of warm mixes, two types of aggregate grading as per MORTH (2013), namely dense bituminous macadam (DBM) and bituminous concrete (BC) have been considered. In this study, initial trials showed possibility of preparation of suitable mixes in temperature range of 110°C-130^{0}C. In order to establish a best suitable temperature, the WMA samples have been prepared in three different mixing temperatures such as 110^{0}C, 120^{0}C and 130^{0}C.

3.2 Materials used

3.2.1 Aggregates

The coarse aggregates and fine aggregates (retained on 0.075 mm IS sieve) inclusive of dust, were collected from a local crusher. For preparation of two types of bituminous mixes (DBM, BC) aggregates gradations were considered as per MORTH (2013), given in Table 3.1 and Table 3.2 respectively. The physical properties of coarse aggregates are given in Table 3.3 and the specific gravity of coarse and fine aggregates are 2.75 and 2.6 respectively.

Table 3.1 Gradation for Bituminous Concrete (BC) (MORTH, 2013)

Sieve size (mm)	Percentage passing
19	100
13.2	79-100
9.5	70-88
4.75	53-71
2.36	42-58
1.18	34-38
0.6	26-38
0.3	18-28
0.15	12-20
0.075	4-10

Table 3.2 Gradation for Dense Bituminous Macadam (DBM) (MORTH, 2013)

Sieve size (mm)	Percentage passing
37.5	100
26.5	90-100
19	71-95
13.2	56-80
4.75	38-54
2.36	28-42
0.3	7-21
0.075	2-8

Table 3.3 Physical properties of coarse aggregates

Property	Test method	Test results
Aggregate Impact Value (%)	IS: 2386 (P IV)	14.3
Aggregate Crushing Value (%)	IS: 2386 (P IV)	13.0
Los Angeles Abrasion Value (%)	IS: 2386 (P IV)	18
Flakiness Index (%)	IS: 2386 (P I)	18.8
Elongation Index (%)		21.5
Water Absorption (%)	IS: 2386 (P III)	0.1

3.2.2 Filler

The materials passing through 0.075 mm IS sieve is are filler. It fills the voids, stiffens the binder and offers better impermeability. In this experimental WMA work, stone dust and cement were used as filler whose specific gravity found in laboratory to be 2.7 and 3.0 respectively.

3.2.3 Binder

Generally bitumen acts as a binding agent to the aggregates, fines and stabilizers the bituminous mixtures. Bitumen must be treated as a visco-elastic material as it exhibits both viscous as well as elastic properties at the normal pavement temperature. At low temperature it behaves like an elastic material and at high temperatures its behaviour is like a viscous fluid. Conventional VG30 grade bitumen, collected from local government depot has been used in this research study to prepare the two types of bituminous mixtures. The physical properties of VG 30 bitumen is presented in table 3.4.

Table 3.4 Physical properties of VG 30 bitumen

Property	Test method	Value
Penetration at 25 °C (0.1 mm)	IS : 1203-1978	67.7
Softening Point °C	IS : 1203-1978	48.5
Specific gravity	IS : 1203-1978	1.03

3.2.4 Bituminous Emulsion

An Emulsion can be defined as the dispersion of small droplets of one liquid in another. Bituminous emulsions generally belong to oil - in -water type where bitumen is dispersed in water with small quantity of emulsifying agent. Chemically stabilized bituminous emulsion has three necessary components bitumen, water and emulsifying agent. The asphalt cement is used for cementing or bonding of aggregates and standing up to traffic, environmental conditions and climate temperature. The emulsifying agent is called surfactant which is chemically composed of large molecules. Some of the benefits of bituminous emulsions are reduce energy needs and fume production, water based emulsions mix easily with aggregates, Emulsion mixes can be mixed on site, in portable plant or at central mixing plant and Emulsion mix overlays improves structural capacity of roads.

According to the setting of emulsion these can be categorised as Rapid Setting Emulsion (RS), Medium Setting Emulsion (MS), and Slow Setting Emulsion (SS).

- Rapid Setting Emulsion (RS) are the least stable emulsion and break rapidly when come in contact with aggregates. This have no ability to mix the aggregates. These are generally used for spray applications.
- Medium Setting Emulsion (MS) are designed to mix with aggregates. Depending on the design medium setting emulsion remain workable from few minutes to several months.
- Slow Setting Emulsion (SS) are designed to work with the fine aggregates to allow for the maximum mixing time and extended workability. These are the most stable emulsion. These can be used in dense graded aggregate bases, soil stabilization and for some slurry seals.

The physical properties of Medium setting emulsion, also collected from local government depot are presented in table 3.5.

Table 3.5 Physical properties of Bituminous Emulsion (MS)

Property	Test method	Test result
Viscosity by Saybolt Furol Viscometer at 50° C (Sec)	IS : 8887-2004	120
Residue by evaporation (%)	IS : 8887-2004	65.4
Residue Penetration at 25° C (0.1 mm)	IS : 8887-2004	84
Residue Ductility at 27° C (cm)	IS : 8887-2004	95

3.3 Preparation of Marshall Samples

After a number of trials, the procedure for mixing of ingredients for the preparation of warm mixes was developed. It was seen that when emulsion- precoated aggregates were used these required a temperature of 110°C -130°C for preparation of suitable bituminous mix. The detailed procedure thus developed is mentioned below.

Required quantities of coarse aggregate, fine aggregate and filler of a specified aggregate gradation are taken in an iron pan. For selection of appropriate filler for a suitable warm mix, initially stone dust and Cement have been used as filler in both types of aggregate grading. Filler resulting maximum stability was decided to be considered for the further study. The required quantity of cationic medium setting emulsion taking into consideration the total residual bitumen content in the emulsion (MS), amounting to 50% of total binder is added to the mix and the ingredients mixed thoroughly are initially kept in the open air for about 9 hours with intermediate stirring. The mix is then kept inside the oven for about 30 min at a selected temperature for preheating and preconditioning at a selected mixing temperature say 110^0C. VG 30 bitumen is also heated separately on a hot plate to a temperature of 130^0 to 140°C. Bitumen is then added to this mix containing precoated aggregates and the ingredients are stirred uniformly and homogenously for 15-20 minutes till a uniform colour is noticed. Care is taken to maintain the mix at the defined temperature, say 110^0C. The same procedure is followed for preparing the warm mix samples at 120°C and 130°C for each type of mix (DBM or BC). Then the mix was transferred to a casting mould. 75 no. of blows were given per each side of the sample. Then each sample was marked and kept separately.

Similarly, more number of Marshall Samples prepared at their optimum binder contents have been prepared for conduct of next set of experiments such as, static indirect tensile test and moisture susceptibility tests. The static indirect tensile test was conducted on Marshall specimens in the loading frame of a Marshall testing apparatus at temperature varying from

5˚C to 40˚C as per the ASTM D 6931-07 (2007). The moisture susceptibility tests of the mixes were investigated in terms of tensile strength ratio and retained stability values.

3.4 Tests on Marshall Samples

3.4.1 Marshall test

Marshall Mix design is a standard laboratory method, which is adopted worldwide for determining and reporting the strength and flow characteristics of bituminous paving mixes. In India, it is a very popular method of characterization of bituminous mixes. This test has also been used by many researchers to test bituminous mixes. This test method is widely accepted because of its simplicity and low of cost. Considering various advantages of the Marshall method it was decided to use this method to determine the Optimum Binder Content (OBC) of the mixes and also study various Marshall Characteristics such as Marshall Stability, flow value, unit weight, air voids etc.

The resistance to plastic deformation of a compacted cylindrical specimen of bituminous mixture is measured when the specimen is loaded diametrically at a deformation rate of 50 mm/min. Here are two major features of the Marshall method of mix design.

(i) Stability, flow tests and

(ii) Voids analysis.

The Marshall stability of the mix is defined as the maximum load carried by the specimen at a standard test temperature of 60°C.

The flow value is the deformation that the test specimen undergoes during loading up to the maximum load.

The mix volumetric of the Marshall samples such as unit weight, air voids were calculated by using the procedure reported by Das and Chakroborty (2003). For constraint of time each and every test on all types of mixes cannot be completed. Hence it was decided to carry out the

next set of experiments such as static indirect tensile test and moisture susceptibility tests on the mixes prepared at their OBC and OEC.

Fig. 3.1 Marshall test under progress

3.4.2 Retained stability test

Retained Stability (RS) is the measure of moisture induced striping in the mix and subsequent loss of stability due to weakened bond between aggregates and binder. The test was conducted following STP 204-22 on the Marshall machine with the normal Marshall samples. The stability was determined after placing the samples in water bath at 60 ℃ for half an hour and 24 hours. The RS value is found out using equation 3.1.

$$\text{Retained stability} = x = \frac{S2 * S1}{2100} \quad (3.1)$$

Where, S2=Soaked stability (after soaking of 24 hours at 60℃)

S1= Standard stability

3.4.3 Static Indirect tensile strength test (ITS)

In this test, a compressive load of 51 mm/minute is applied on a cylindrical Marshall specimen along a vertical diametrical plane through two curved strips made up of stainless steel, 13 mm (1/2") wide, 13 mm deep and 75 mm long, whose radius of curvature is same as that of the specimen were used to provide a uniform loading width which produces a nearly uniform stress distribution. The inside diameter of the strip made was same as that of a Marshall sample (102 mm**).**The sample was kept in the Perspex water bath (270 mm *250 mm *195mm)maintained at the required temperature for minimum 1/2 hours before test, and the same temperature was maintained during test. The Perspex water bath maintained at the same test temperature was placed on the bottom plate of the Marshall apparatus. The sample was then kept inside the Perspex water bath within the two loading strips. Loading rate of 51 mm/minute was adopted. This loading configuration developed a relatively uniform tensile stress perpendicular to the direction of the applied load and along the vertical diametric plane and the specimen failed by splitting along the vertical diameter. The below equation applies for 4 inch diameter samples having 0.5 inch curved loading strip and for 6 inch diameter samples having a 0.75 inch curved loading strip .

The tensile strength of the specimen was calculated according to ASTM D 6931 (2007) from the failure load noted from the dial gauge of the proving ring.

$$ST = \frac{2*\mathrm{P}}{¶*D*T} \qquad (3.2)$$

where

ST = Indirect Tensile Strength, kPa

P = Maximum Load, kN

T = Specimen height before testing, mm

D = Specimen Diameter, mm

The test temperature was varied from 5°C to 40°C at increment of 5°C. The tensile strength was reported as the average of the three test results.

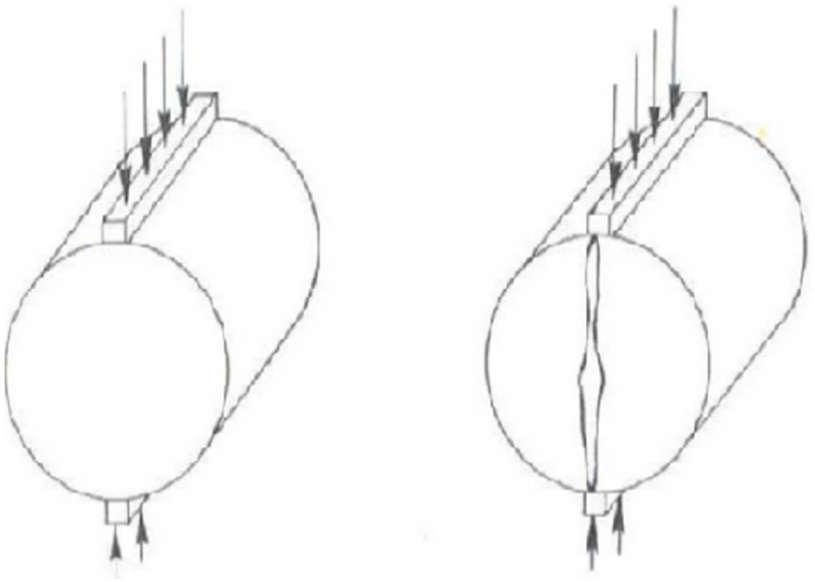

Fig. 3.2 loading configuration for indirect tensile strength (ITS) test

(a) Specimen tested at 5°C (b)Specimen tested at 10°C

Fig. 3.3 Samples tested for ITS at different test temperatures

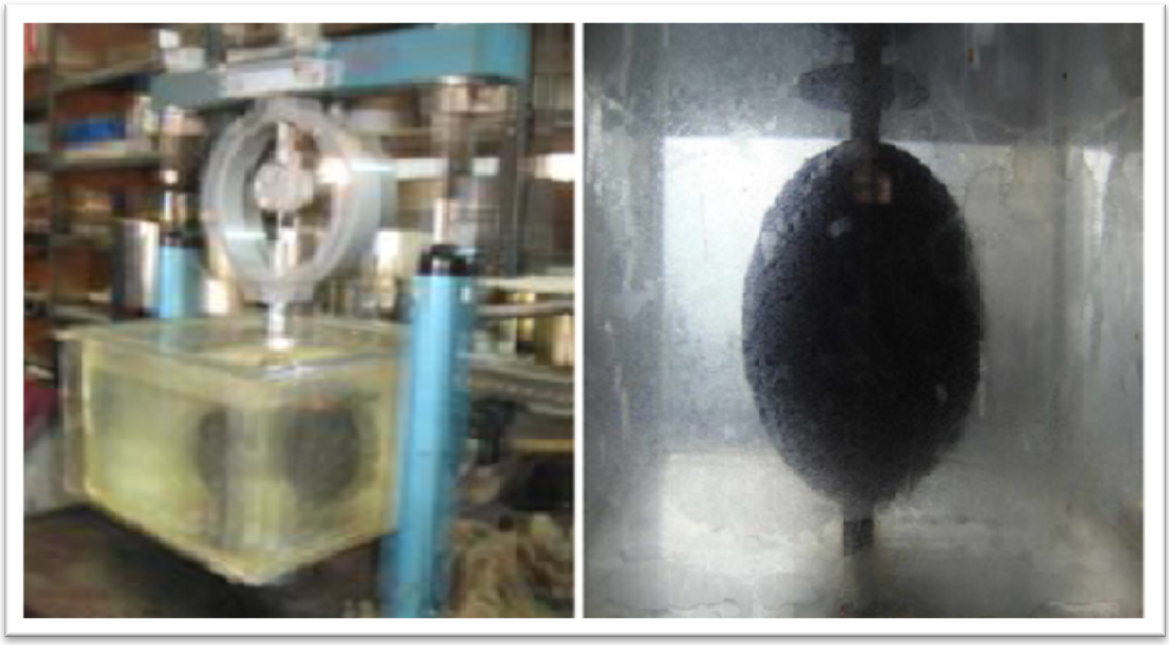

Fig. 3.4 Close view of indirect tensile strength test on progress

3.3.4 Tensile strength ratio

The tensile strength ratio of asphalt mixes is an indicator of their resistance to moisture susceptibility. The test was carried out by loading a Marshall specimen with compressive load acting along the vertical diametric-loading plane. The test was conducted followed by AASHTO T 283 at 25°C temperature and the tensile strength calculated from the load at which the specimen fails is taken as the dry tensile strength of the asphalt mix. The specimens were then placed in a water bath maintained at 60°C for 24 hours and then immediately placed in an environmental chamber maintained at 25°C for two hours. These conditioned specimens were then tested for their tensile strength. The ratio of the indirect tensile strength (ITS) of the water-conditioned specimens to that of dry specimens is the tensile strength ratio.

$$\text{Tensile strength ratio (TSR)} = \frac{\text{ITS Of conditioned specimen set}}{\text{ITS of unconditioned specimen set}} * 100 \qquad (3.3)$$

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

In this chapter the results of tests as per the experimental investigations described in the previous chapter have been presented, analyzed and discussed. This chapter is mainly divided into four sections. First section deals with Marshall parameters used for volumetric analysis. Second section refers to selection of setting time of emulsion used in preparation of warm mixes. It also provides selection of appropriate type of filler, i.e. among stone dust and cement for the emulsion bitumen warm mix design and selection of setting time of medium setting emulsion for the mix design after various trial sections, after analyzing various Marshall parameters of each trial sections. The third section deals with the study of Marshall properties with the objective of calculation of optimum bitumen Content (OBC) and bitumen-emulsion composition in respect of DBM and BC warm mixes prepared separately at each mixing temperature of 110°C, 120°C or 130°C and deciding the suitable temperature for the DBM and BC warm mix after proper analysis of the Marshall properties of each mixing temperature. Finally, the fourth section deals with the results of other engineering properties of the mixes such as Indirect Tensile Strength and resistances to moisture induced damages in terms of tensile strength ratio (TSR) and retained stability (RS) test.

4.2 Parameters Used

In terms of volumetric in warm mixture analysis as per Das and Chakroborty (2010), the definitions and other formulae used in calculations hereafter are as follows:

Bulk Specific Gravity of aggregate (G_{sb})

$$G_{sb} = \frac{M_{agg}}{\text{volume of (agg.mass+airvoid in agg.+absorb bitumen)}} \quad (4.1)$$

Where M_{agg} = mass of aggregate

Effective specific gravity of aggregate(G_{se})

$$G_{se} = \frac{M_{agg}}{\text{volume of (agg.mass+air void in aggregate)}} \quad (4.2)$$

Where M_{agg}= mass of aggregate

$$G_{se} = (M_{mix} - M_b) / \left(\frac{M_{mix}}{G_{mm}} - \frac{M_b}{G_b}\right) \quad (4.3)$$

where M_b = mass of bitumen used in mix

G_b = specific gravity of bitumen

Apparent Specific Gravity (G_a)

$$G_a = \frac{M_{agg}}{\text{volume of aggregate mass}} \quad (4.4)$$

Theoretical Maximum Specific Gravity of Mix (G_{mm})

$$G_{mm} = \frac{M_{mix}}{\text{volume of (mix}-\text{air voids)}} \quad (4.5)$$

Bulk Specific Gravity of Mix (G_{mb})

$$G_{mb} = \frac{M_{mix}}{\text{bulk volume of mix}} \quad (4.6)$$

Air Voids (VA)

$$VA = \left[1 - \frac{G_{mb}}{G_{mm}}\right] * 100 \quad (4.7)$$

Voids in Mineral Aggregates (VMA)

$$VMA = \left[1 - \frac{G_{mb}}{G_{mm}} * P_S\right] *100 \quad (4.8)$$

Where P_s = percentage of aggregate present by total mass of mix

Voids Filled With Bitumen (VFB)

$$VFB = \left[\frac{VMA-VA}{VMA}\right] *100 \quad (4.9)$$

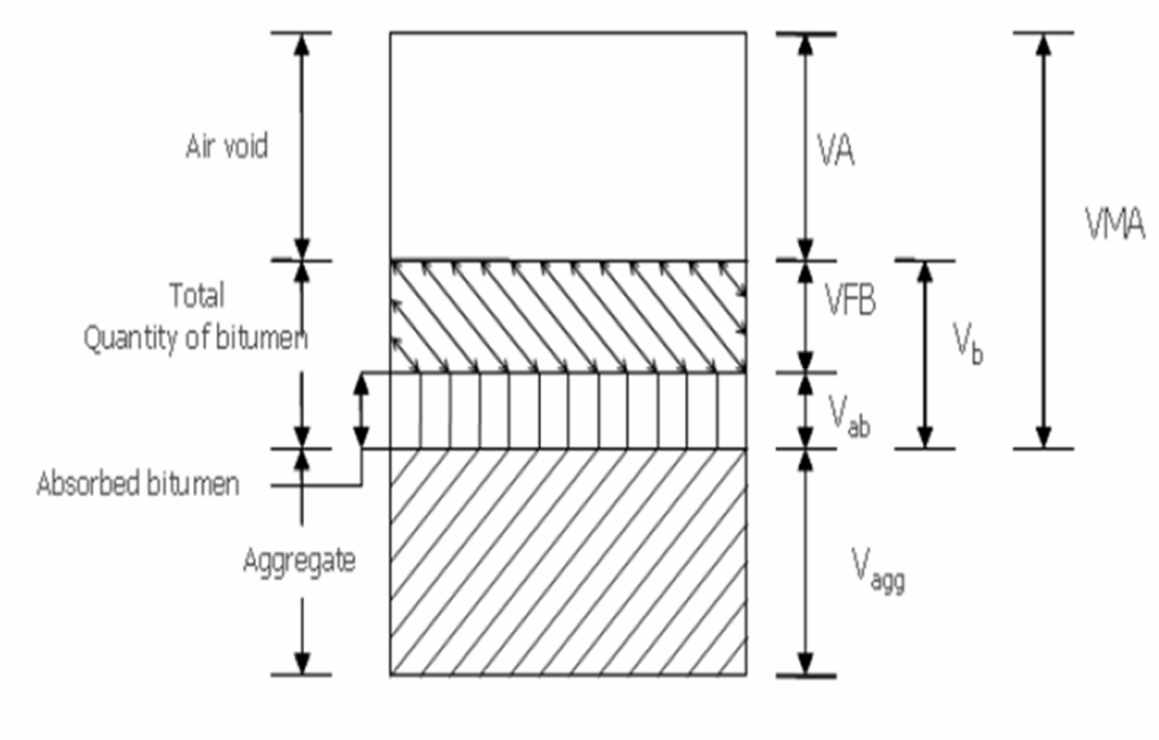

Fig. 4.1 Phase Diagram of bituminous mix (Das and Chakroborty 2010)

4.3 Selection of Setting Time of Emulsion and Type of Filler

4.3.1 Marshall properties based on setting times of Emulsion

In this study, warm mix is proposed to be prepared by using both medium setting emulsion (actual residual bitumen content) and VG 30 as binder in equal proportions. As the setting

time of medium setting emulsion used plays a pivotal role in improving the mix characteristics, Marshall properties on mixes with DBM grading and cement as filler, prepared with varying emulsion setting times have been studied. Emulsion setting times of 3 hrs, 6 hrs, 9hrs, 10 hrs and 12 hrs was considered for the sample preparation and emulsion mixed samples were compacted at the specified time interval. The descriptions for preparation of warm mixes have been given in later paragraphs. The results of the Marshall tests are presented in the figures 4.2 to 4.7 given below.

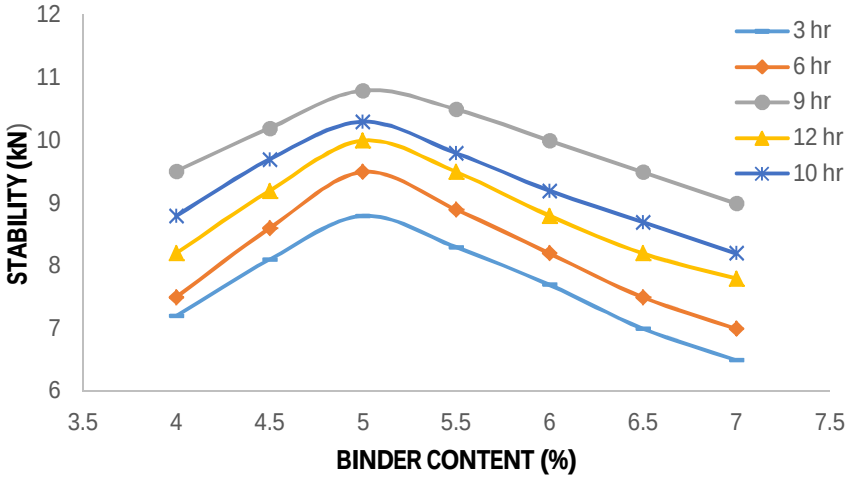

Fig. 4.2 Stability vs binder content for setting times of medium setting emulsion

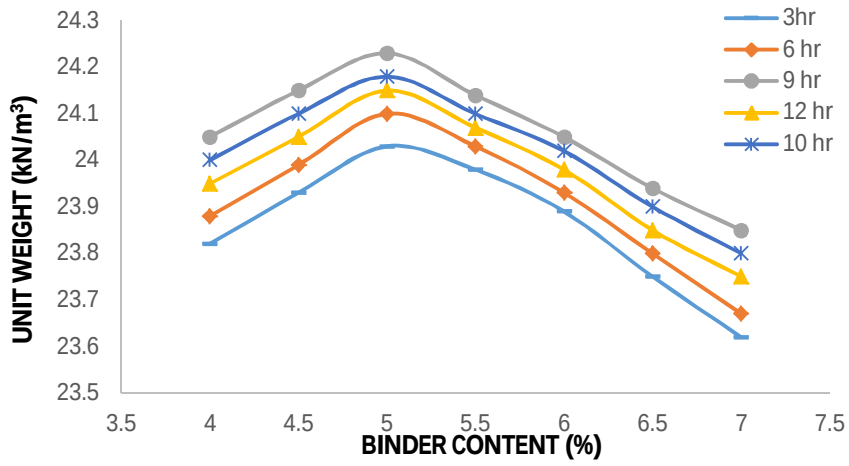

Fig. 4.3 Unit weight vs binder content for setting times of medium setting emulsion

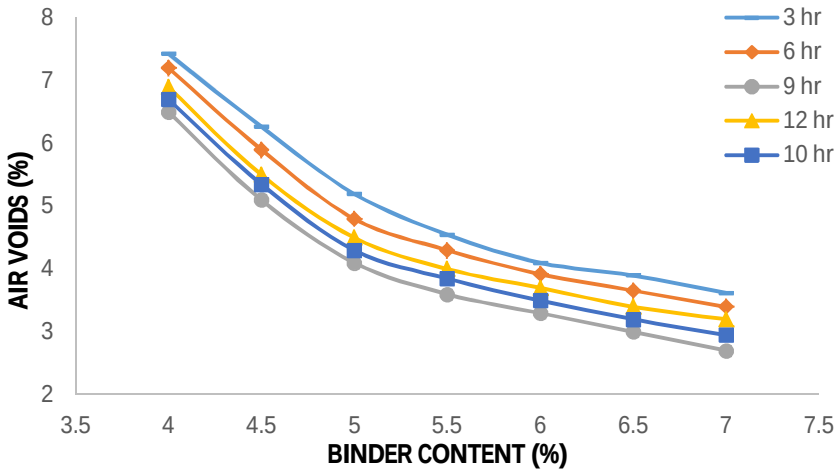

Fig. 4.4 Air voids vs binder content for setting times of medium setting emulsion

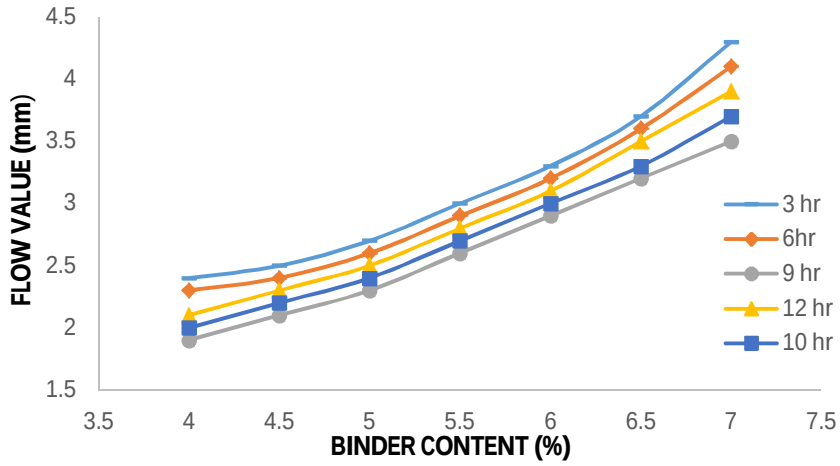

Fig. 4.5 Flow value vs binder content for setting times of medium setting emulsion

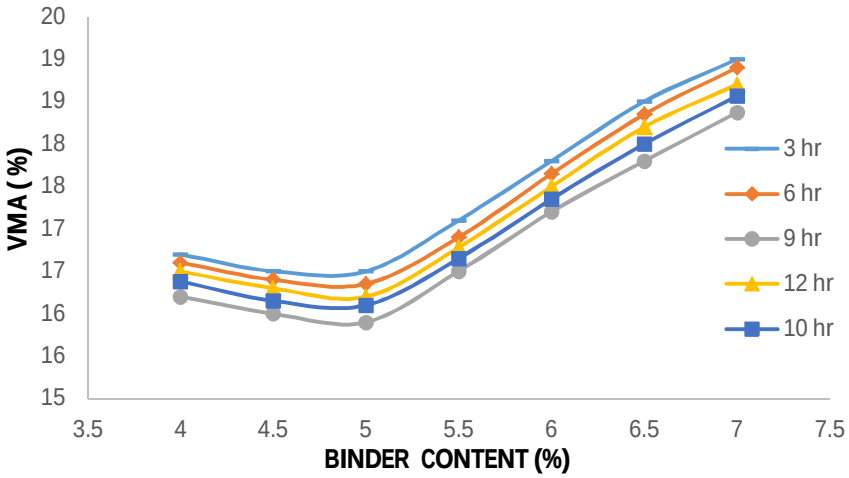

Fig. 4.6 Voids in mineral aggregates (VMA) vs binder content for setting times of emulsion

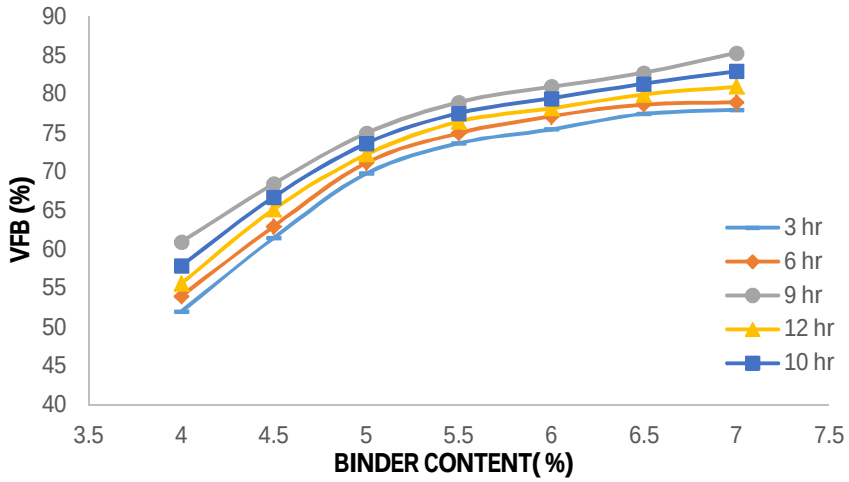

Fig. 4.7 Voids filled with bitumen (VFB) vs binder content for setting times of emulsion

The Marshall properties in general are observed to improve with increasing setting time of emulsion up to 9hrs, after which the properties decrease, although the residual bitumen obtained after 9hrs/10hrs and 12hrs of setting time of emulsion may be the same. It is observed that the decrease/ change in properties is only marginal. It is due to the fact that while the viscosity of the residual bitumen used to coat the aggregates increases, the same used at elevated temperature is much lower, causing incompatibility of viscosity of the two different bituminous binders in the same mix.

4.3.2 Selection of filler type for warm mix

Stone dust and cement have been used separately as filler for the preparation of warm mix with DBM grading using varying emulsion binder contents. In order to ascertain the effects of filler type on Marshall Characteristics of warm mixes, samples have been prepared and tested for the same properties. The results of Marshall Tests in respect of mixes with both types of fillers are presented in figures from 4.8 to 4.13. It is observed that cement filler offers better properties in terms of stability, unit weight, air voids and flow value. Hence, in further works cement filler has been used for the preparation of warm mixes using various emulsion binder contents.

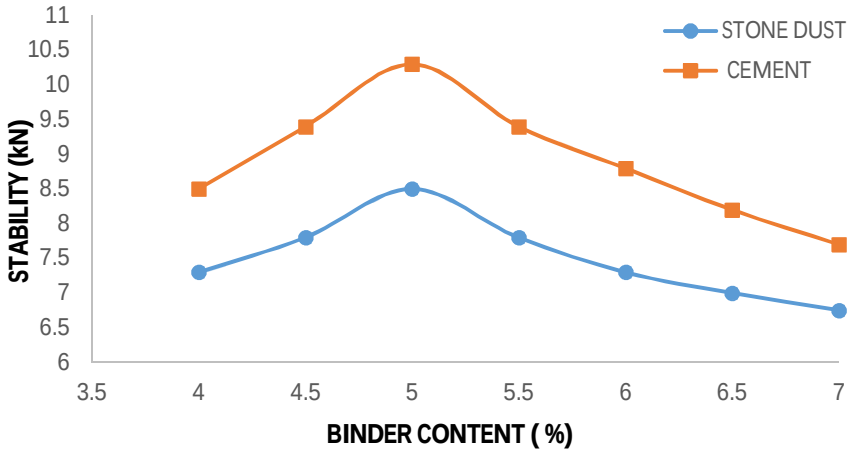

Fig. 4.8 Stability vs binder content for two different types of filler

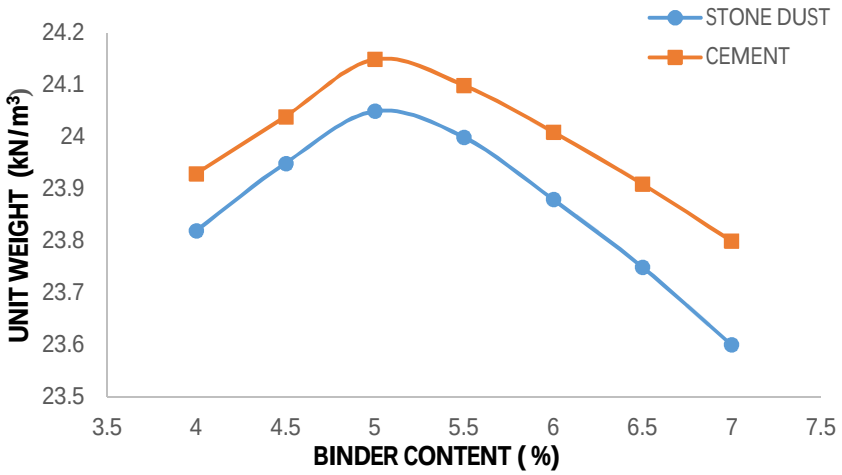

Fig. 4.9 Unit weight vs binder content for two different types of filler

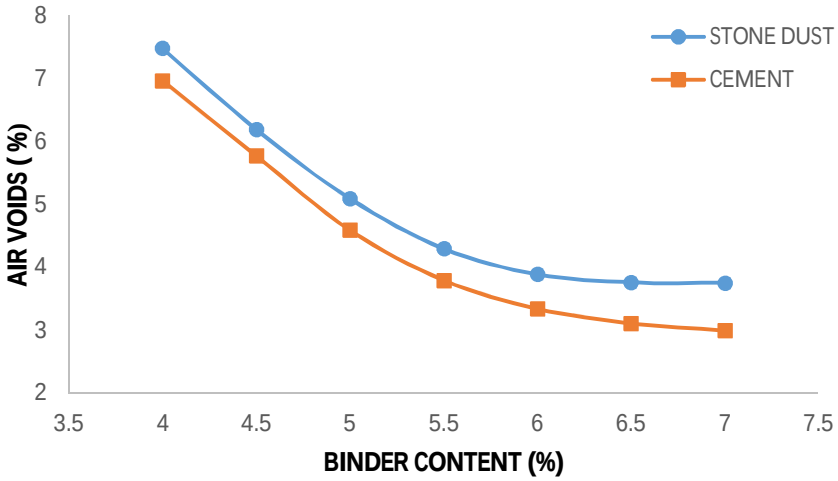

Fig. 4.10 Air voids vs binder content for two different types of filler

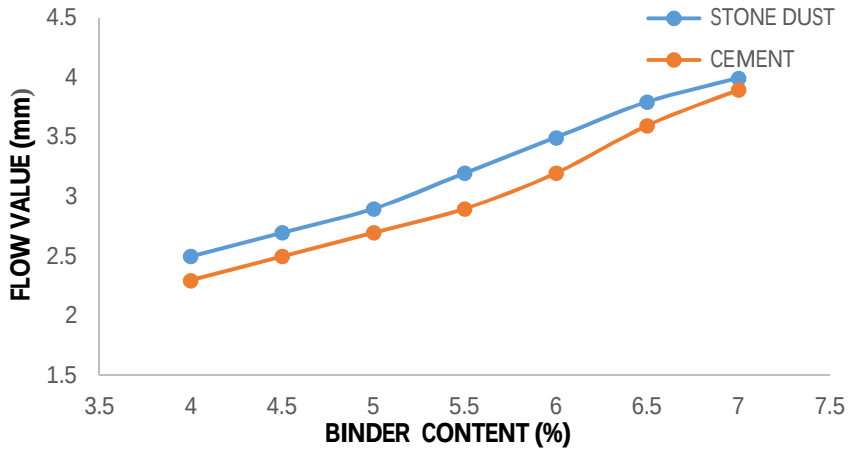

Fig. 4.11 Flow value vs binder content for two different types of filler

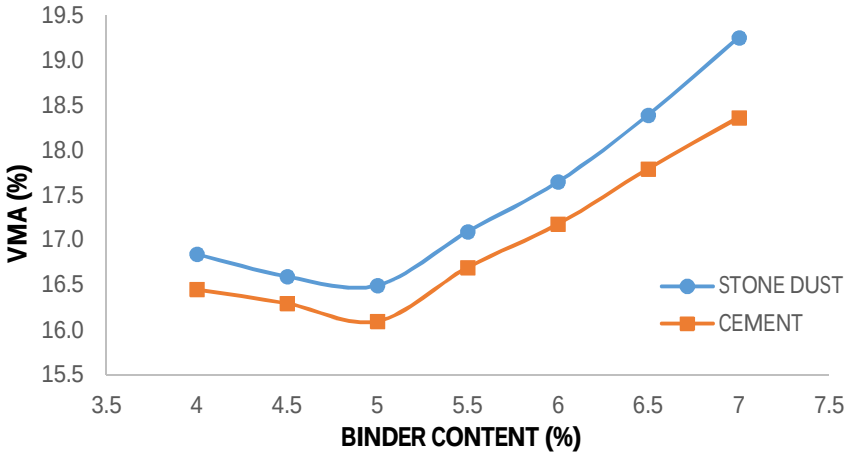

Fig. 4.12 Voids in mineral aggregates (VMA) vs. binder content for two different types of filler

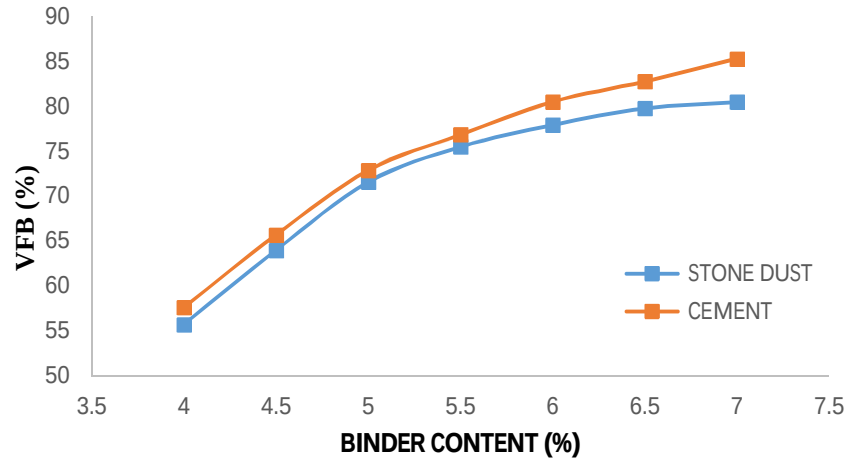

Fig. 4.13 Voids filled with bitumen (VFB) vs binder content for two different types of filler

4.4 Marshall Characteristics of warm mixes

4.4.1 Effect of emulsion composition and temperature of preparation on Marshall Properties for DBM warm mixes

Initial trials showed possibility of development of warm mixes in temperature range of 110°C-130°C and bitumen-emulsion ratio of 1:1 and more. In order to assess the best combination of temperature and bitumen-emulsion ratio, DBM warm mixes are prepared with different bitumen-emulsion concentrations at a particular binder content such as 50B:50E, 60B:40E, 70B:30E, 80B:20E, 90B:10E and100B:0E and each at three different temperatures namely 110°C, 120°C and 130°C. The results of Marshall Test on such varying mixes are presented in the following figures below. The optimum binder content (OBC) obtained for 110°C is 5% for 70B:30E, 120° C is 5.1% for 80B:20E and 130° C is 5.4% for 90B:10E binder contents.

4.4.1.1 Effect of different bitumen emulsion composition on Marshall Properties for warm DBM mix samples prepared at 110^0C

The variation of important Marshall Properties such as stability, unit weight, flow value, air voids ,voids filled with mineral aggregate (VMA), voids filled with bitumen (VFB) for DBM warm mixes prepared at 110^0C are shown in Figs 4.14 to 4.19.It is observed that the trends of variations of Marshall Properties with binder content are similar to normal HMA. It is seen that as usual stability and unit weight increase with binder content up to a certain value say 5% and then decrease. The highest values of stability and unit weight is obtained at their OBC content i.e. 5% similarly, the flow value and air voids respectively increases and decreases with binder content. It is observed that first VMA decreases up to 5% binder content and then it increases at sharp rate with increase in bitumen concentration in mixes. It is observed that VFB values of different mixes increase at sharp rate with increase in binder content. The optimum bitumen-emulsion composition is seen to be 70B:30E and optimum binder content in the mix is observed to be 5%.

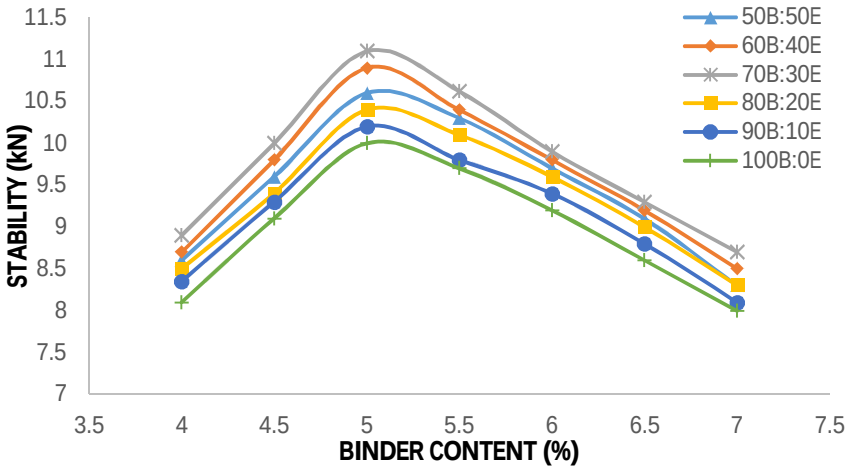

Fig. 4.14 Stability vs binder content for mixes prepared at 110°C

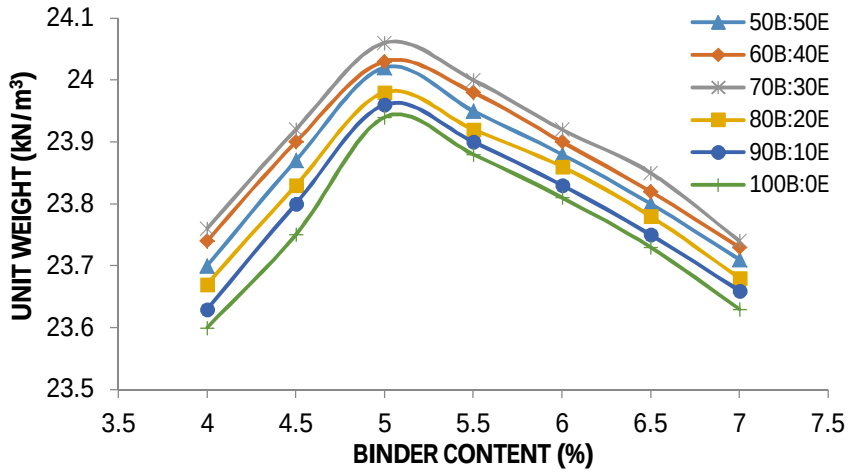

Fig. 4.15 Unit weight vs binder content for mixes prepared at110°C

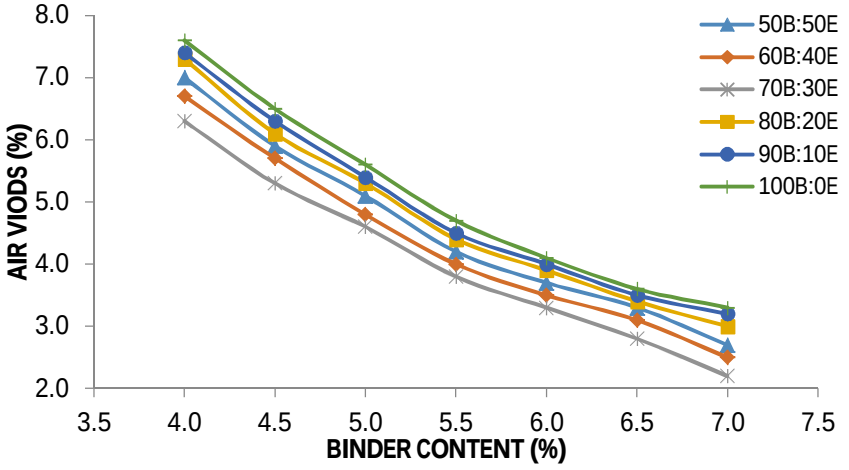

Fig. 4.16 Air voids vs binder content for mixes at 110°C

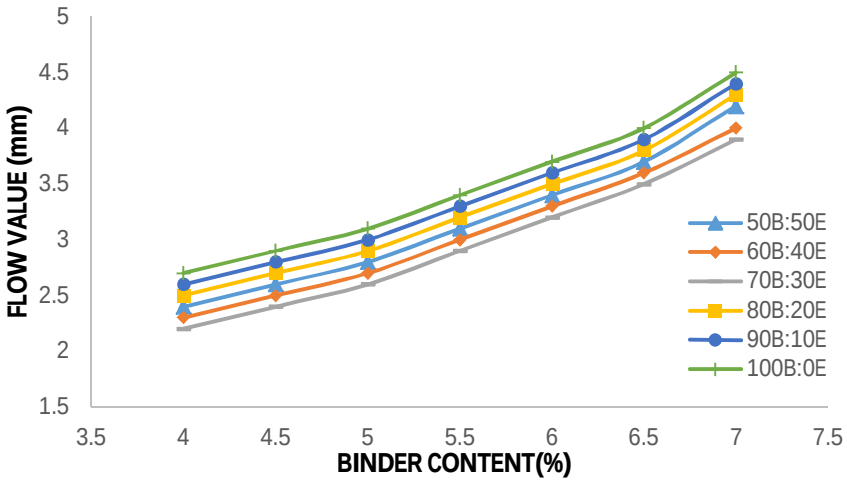

Fig. 4.17 Flow value vs binder content for mixes at 110°C

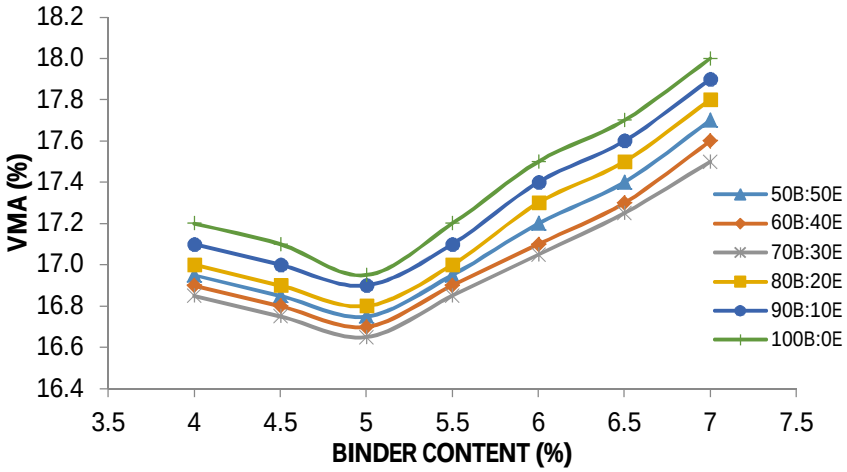

Fig. 4.18 Voids in mineral aggregates (VMA) vs binder content for mixes at 110°C

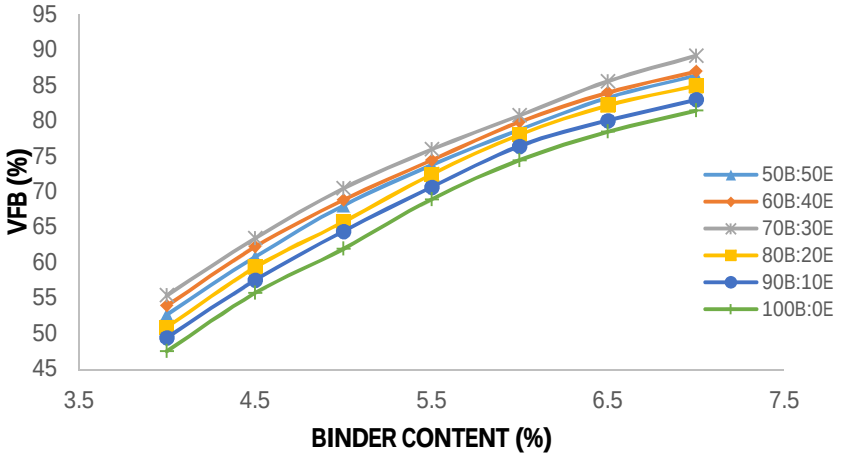

Fig. 4.19 Voids filled with bitumen (VFB) vs binder content for mixes at 110°C

4.4.1.2 Effect of different bitumen emulsion composition on Marshall Properties for warm DBM samples prepared at 120^0C

The variations of important Marshall Properties such as stability, unit weight, flow value, air voids, voids filled with mineral aggregate (VMA), voids filled with bitumen (VFB) for DBM warm mixes prepared at 120^0C are shown in Figures 4.20 to 4.25.It is observed that the trends of variations for Marshall Properties with different binder content are similar to normal HMA. The stability, unit weight values increases to 5%, 5.5% binder content it shows highest stability and unit weight values for 80B:20E binder content then the value decreases gradually. The flow value and air voids respectively increases and decreases with binder content. It is observed that first VMA decreases up to 5.5% binder content and then it increases at sharp rate with increase in bitumen concentration in mixes. Similarly VFB values of different binder content increase at sharp rate with increase in binder content. The OBC of the mix obtained is 5.1% with respect to 80B:20E binder composition.

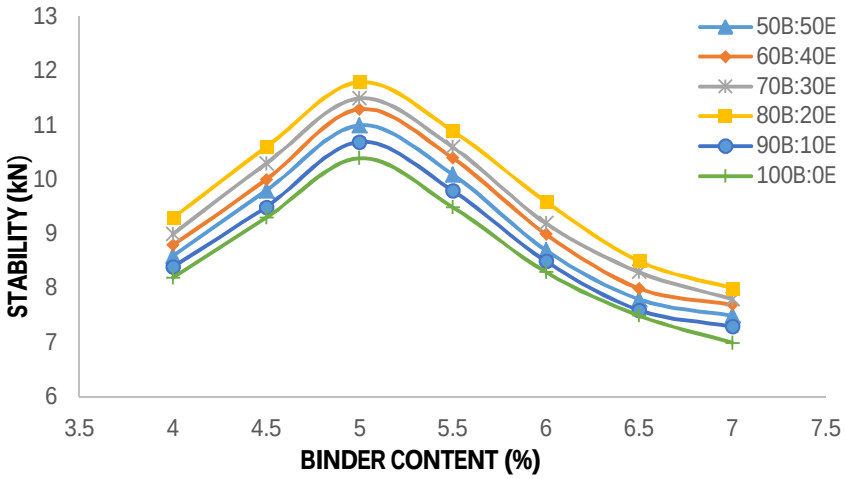

Fig. 4.20 Stability vs binder content for mixes prepared at 120°C

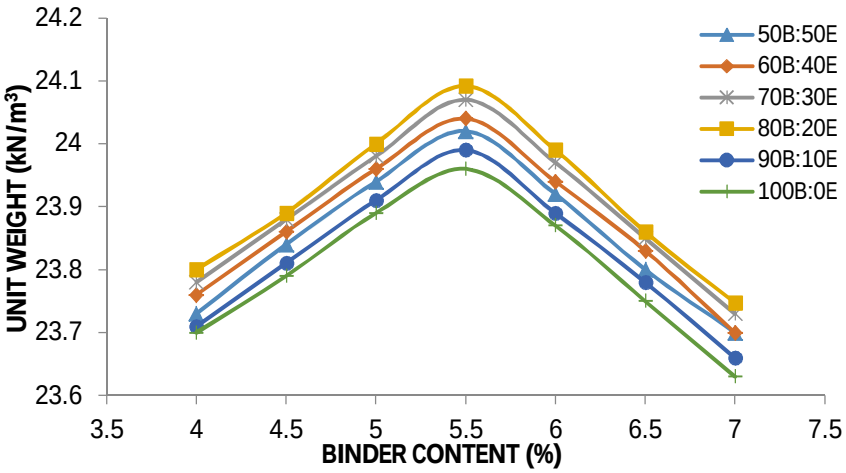

Fig. 4.21 Unit weight vs binder content for mixes prepared at 120°C

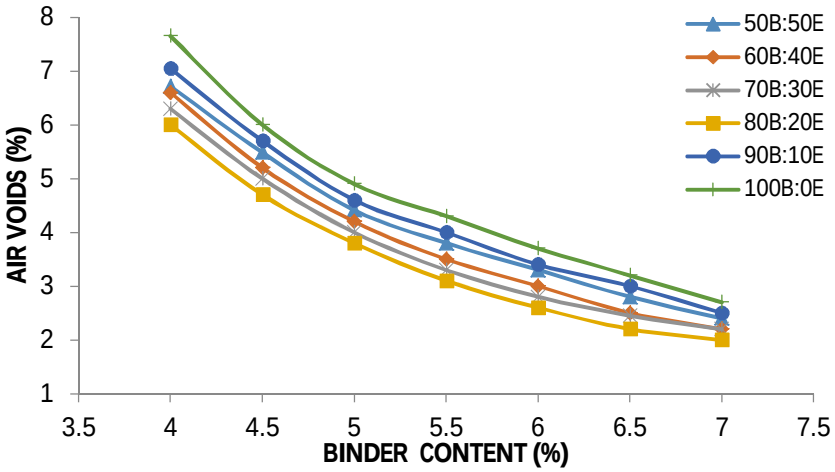

Fig. 4.22 Air voids vs binder content for mixes at 120°C

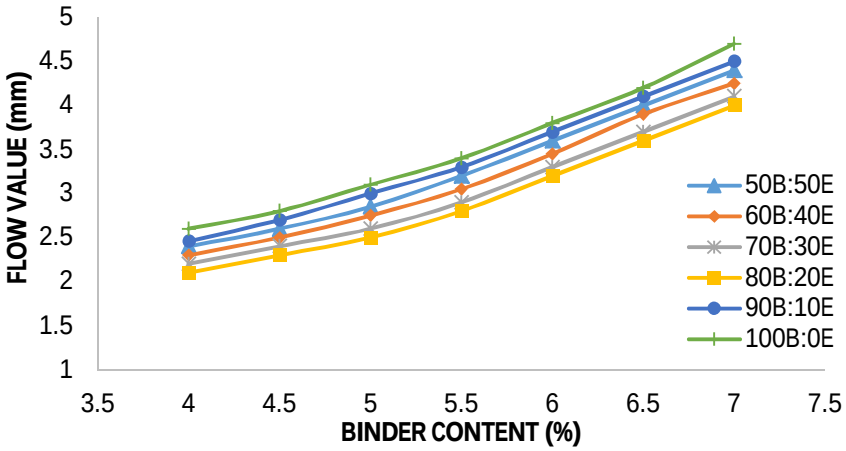

Fig. 4.23 Flow value vs binder content for mixes at 120°C

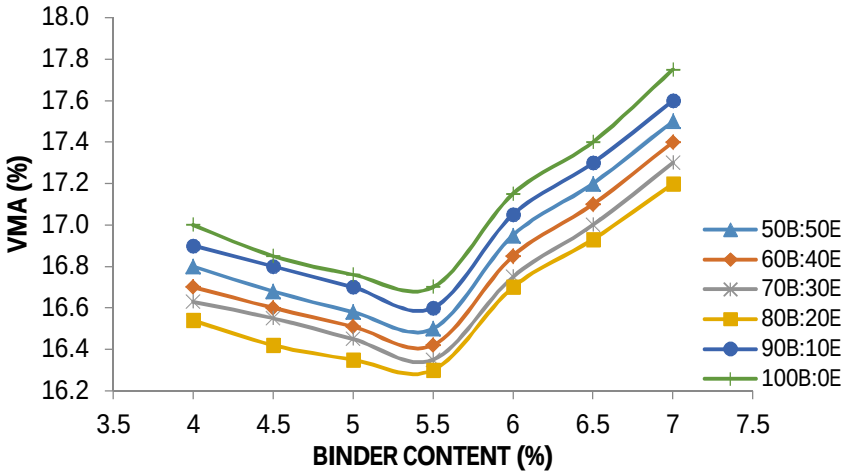

Fig. 4.24 Voids in mineral aggregates (VMA) vs binder content for mixes at 120°C

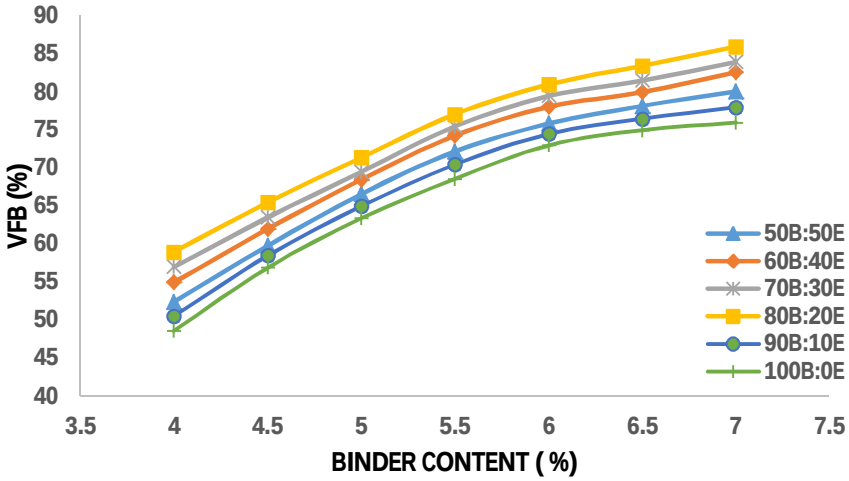

Fig. 4.25 Voids filled with bitumen (VFB) vs binder content for mixes at 120°C

4.4.1.3 Effect of different bitumen emulsion composition on Marshall Properties for warm DBM samples prepared at 130^0C

The variations of important Marshall Properties such as stability, unit weight, flow value, air voids, voids filled with mineral aggregate (VMA), voids filled with bitumen (VFB) for DBM warm mixes prepared at 120^0C are shown in Figures 4.26 to 4.31.It is observed that the trends of variations for Marshall Properties with different binder content are similar to normal HMA. The stability, unit weight values increases to 5%, 5.5% binder content it shows highest stability and unit weight values for 80B:20E binder content then the value decreases gradually. The flow value and air voids respectively increases and decreases with binder

content. It is observed that first VMA decreases up to 5.5% binder content and then it increases at sharp rate with increase in bitumen concentration in mixes. Similarly VFB values of different binder content increase at sharp rate with increase in binder content. The OBC obtained is 5.4% for the optimum 90B:10E binder composition.

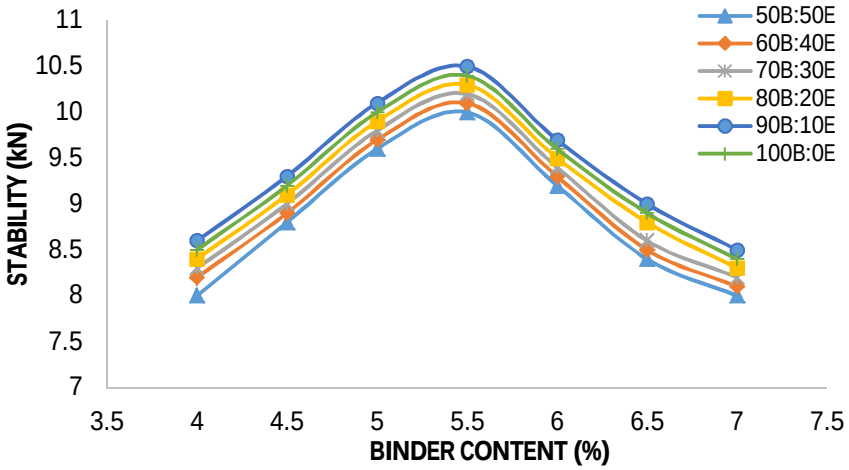

Fig. 4.26 Stability vs binder content for mixes prepared at 130°C

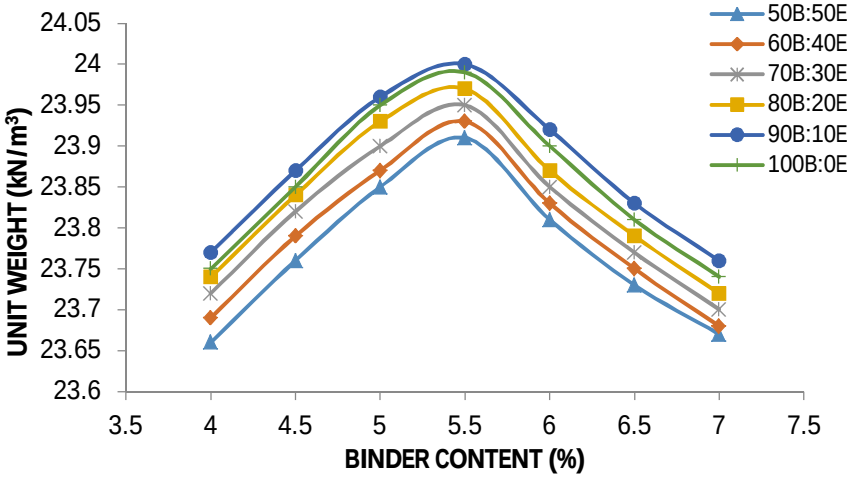

Fig. 4.27 Unit weight vs binder content for mixes prepared at130°C

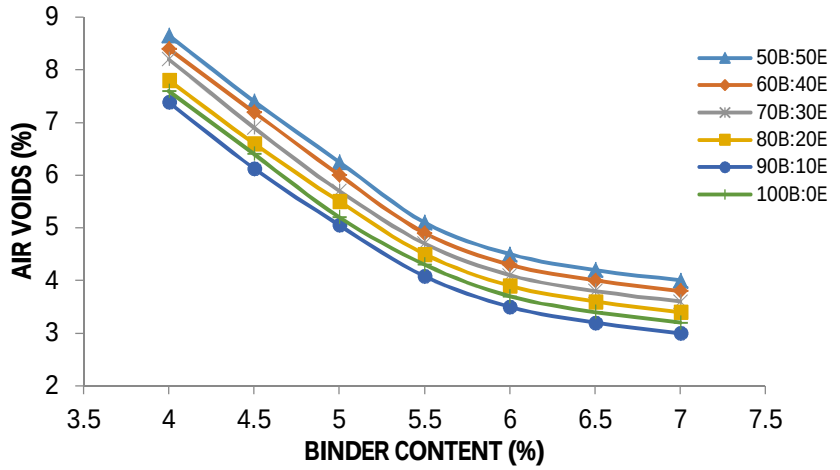

Fig. 4.28 Air voids vs binder content for mixes at 130°C

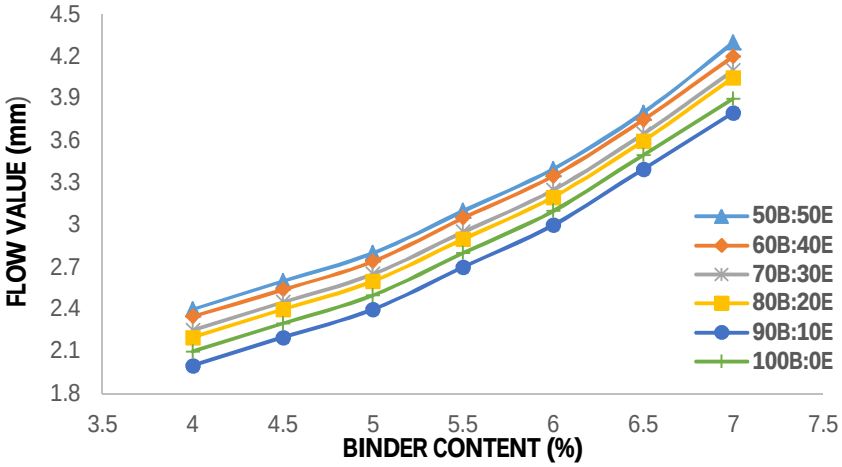

Fig. 4.29 Flow value vs binder content for mixes at 130°C

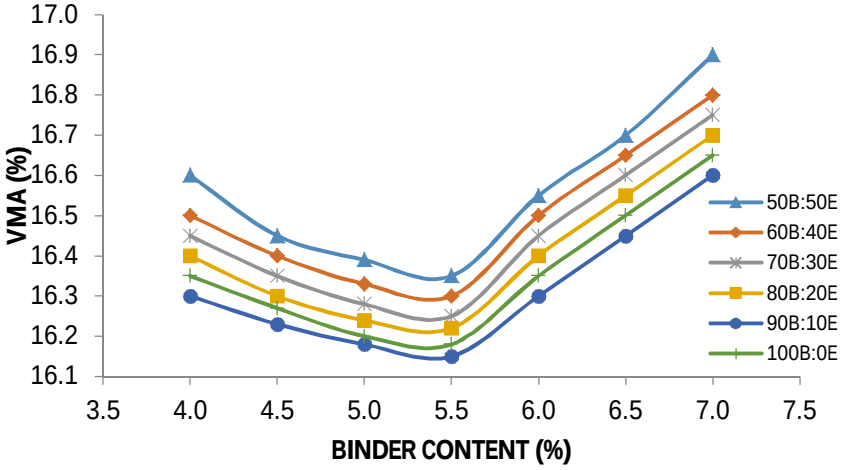

Fig. 4.30 Voids in mineral aggregates (VMA) vs binder content for mixes at 130°C

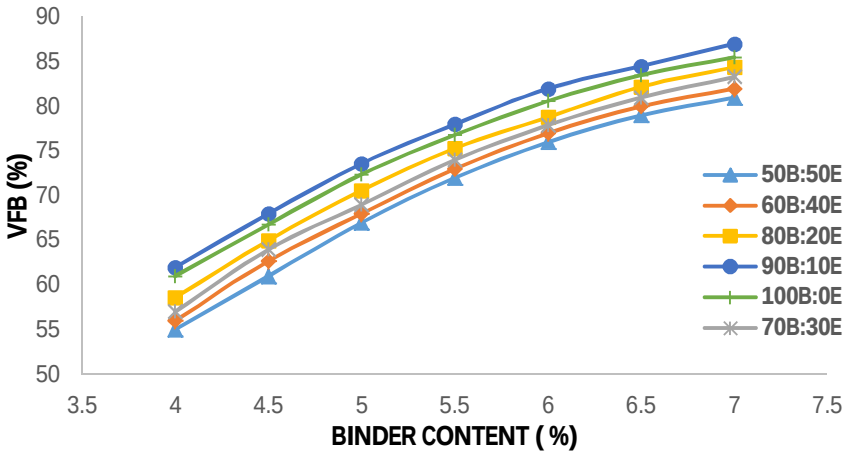

Fig. 4.31 Voids filled with bitumen (VFB) vs binder content for mixes at 130°C

4.4.2 Effect of different bitumen emulsion composition on Marshall Properties for BC Warm Mixes

In the similar manner, BC warm mixes have been prepared at a particular binder content with different bitumen-emulsion concentrations such as 50B:50E, 60B:40E, 70B:30E, 80B:20E, 90B:10E and100B:0E and each at three different temperatures namely 110°C, 120°C and 130°C, are presented below.

4.4.2.1 Effect of different bitumen emulsion composition on Marshall Properties for warm BC samples prepared at 110^0C

The variations of important Marshall Properties such as stability, unit weight, flow value, air voids, voids filled with mineral aggregate (VMA), voids filled with bitumen (VFB) for BC warm mixes prepared at 110^0C are shown in Figures 4.32 to 4.37.It is observed that the trends of variations for Marshall Properties with different binder content are similar to normal HMA. The stability, unit weight values increases to 5% binder content it shows highest stability and unit weight values for 60B:40E binder content then the value decreases gradually. The flow value and air voids respectively increases and decreases with binder content. It is observed that first VMA decreases up to 5% binder content and then it increases at sharp rate with increase in bitumen concentration in mixes. Similarly VFB values of

different binder content increase at sharp rate with increase in binder content. The OBC obtained is 5.1 % for 60B:40E binder content.

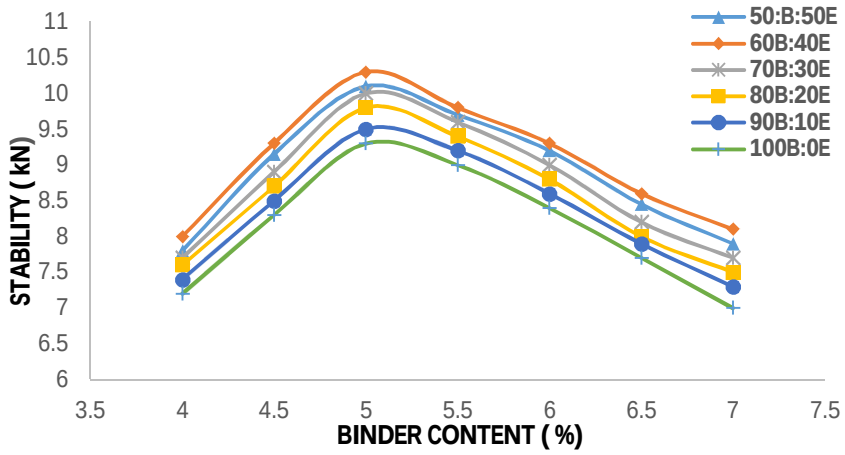

Fig. 4.32 Stability vs binder content for mixes prepared at 110°C

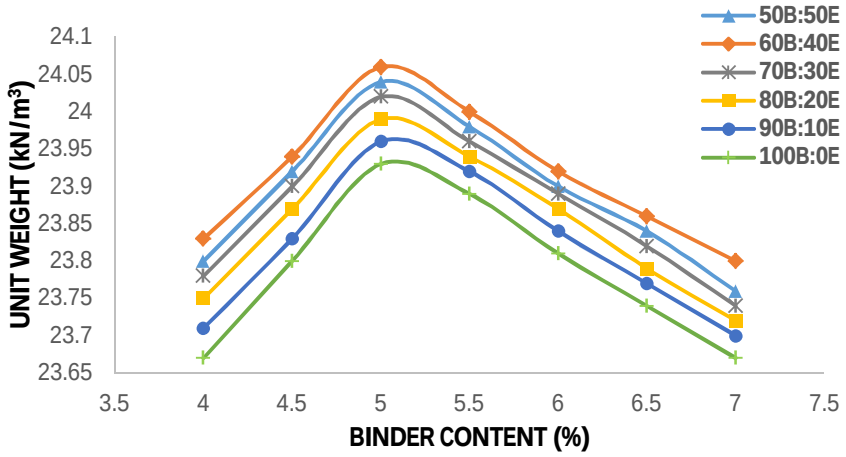

Fig. 4.33 Unit weight vs binder content for mixes prepared at110°C

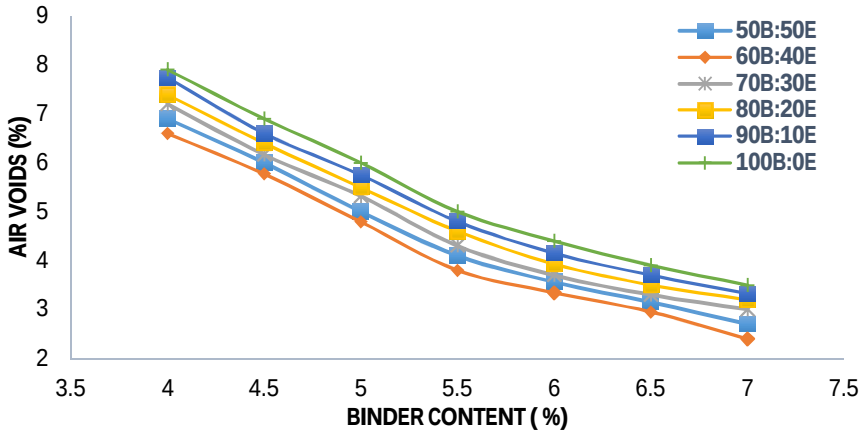

Fig. 4.34 Air voids vs binder content for mixes at 110°C

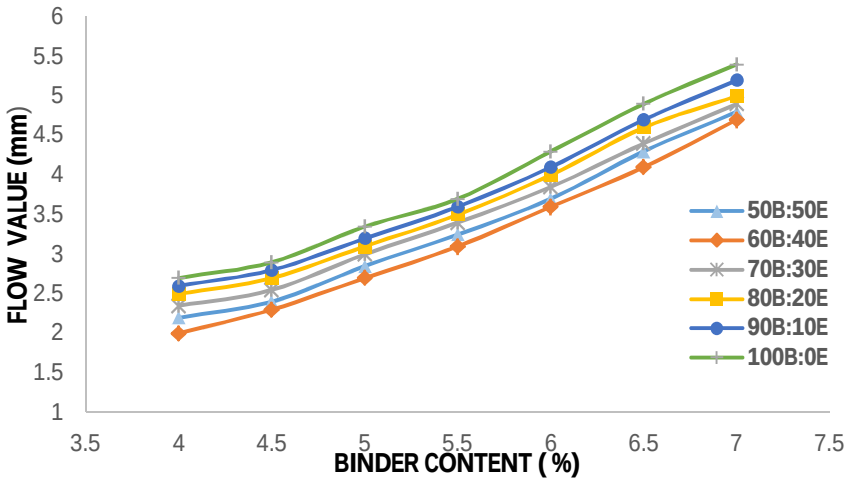

Fig. 4.35 Flow value vs binder content for mixes at 110°C

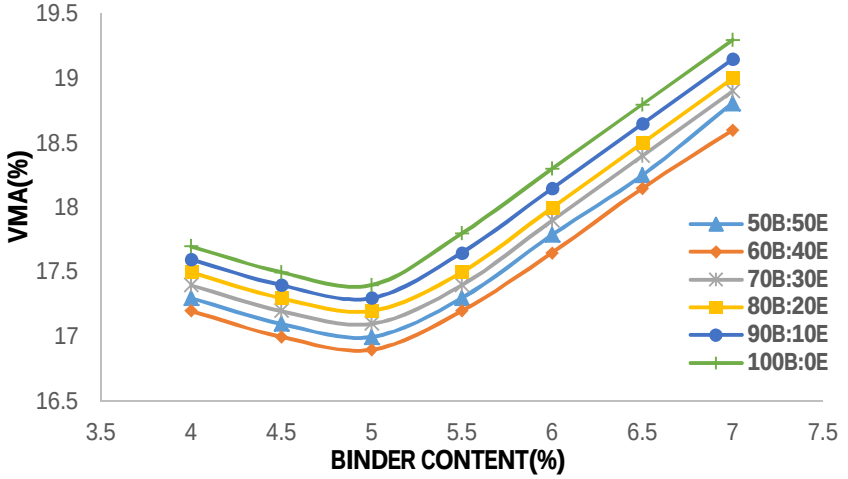

Fig. 4.36 Voids in mineral aggregates (VMA) vs binder content for mixes at 110°C

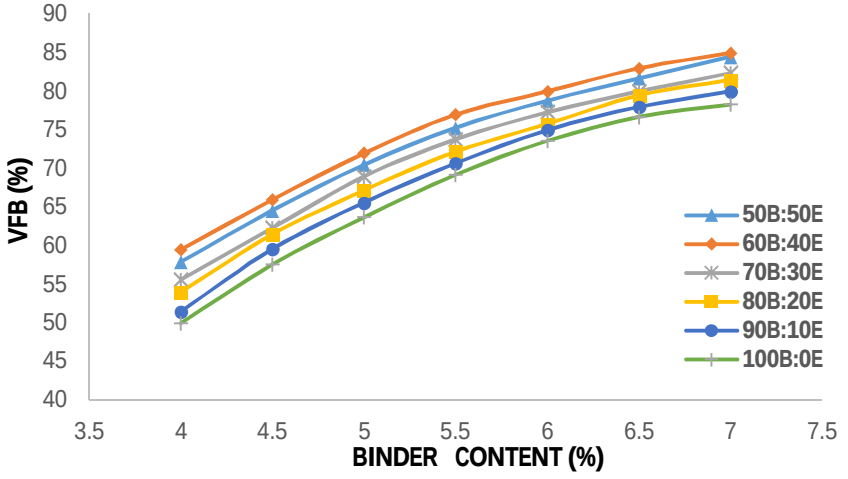

Fig. 4.37 Voids filled with bitumen (VFB) vs binder content for mixes at 110°C

4.4.2.2 Effect of different bitumen emulsion composition on Marshall Properties for warm BC samples prepared at 120^0C

Some important variations of Marshall Properties such as stability, unit weight, flow value, air voids, voids filled with mineral aggregate (VMA), voids filled with bitumen (VFB) for BC warm mixes prepared at 120^0C are shown in Figures 4.38 to 4.43.It is observed that the trends of variations for Marshall Properties with different binder content are similar to normal HMA. The stability, unit weight values increases to 5% binder content it shows highest stability and unit weight values for 70B:30E binder content then the value decreases gradually. The flow value and air voids respectively increases and decreases with binder content. It is observed that first VMA decreases up to 5% binder content and then it increases at sharp rate with increase in bitumen concentration in mixes. Similarly VFB values of different binder content increase at sharp rate with increase in binder content. The OBC obtained is 4.9% for 70B:30E binder content.

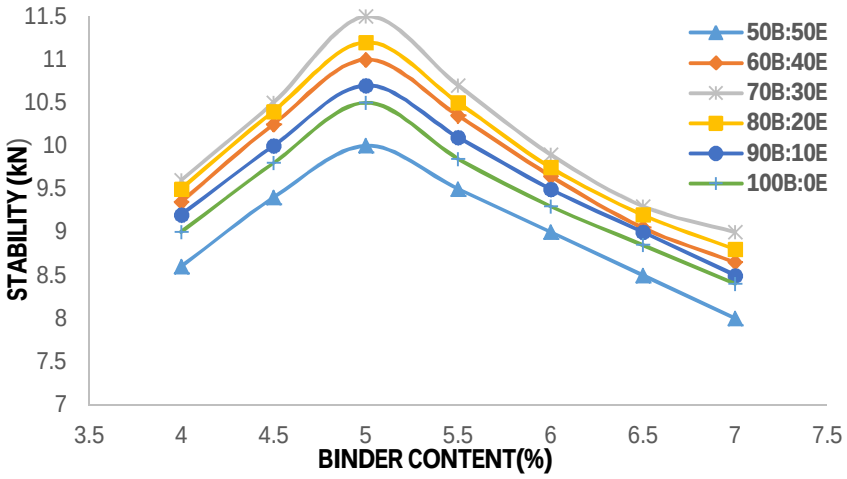

Fig. 4.38 Stability vs binder content for mixes prepared at 120°C

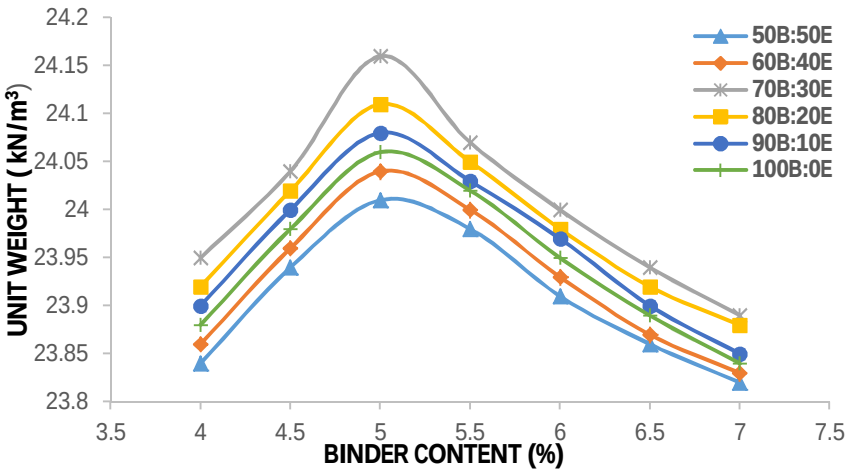

Fig. 4.39 Unit weight vs binder content for mixes prepared at120°C

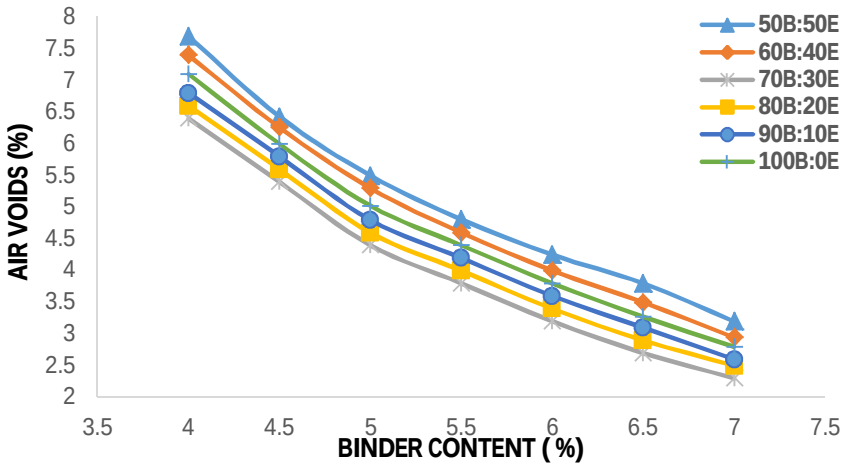

Fig. 4.40 Air voids vs binder content for mixes at 120°C

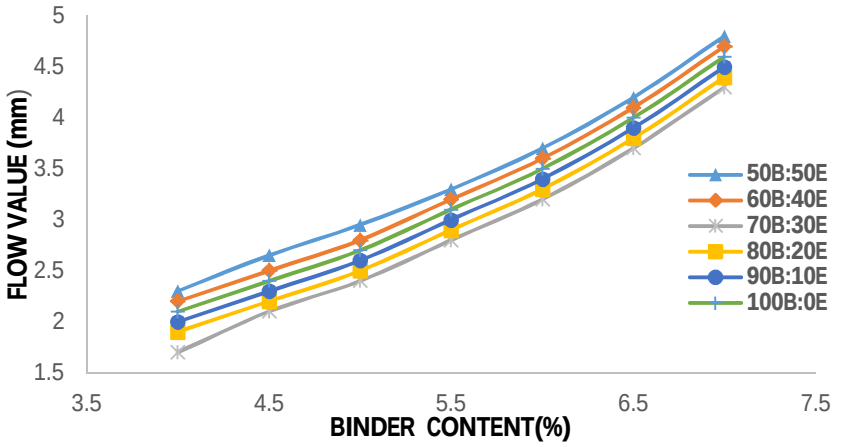

Fig. 4.41 Flow value vs binder content for mixes at 120°C

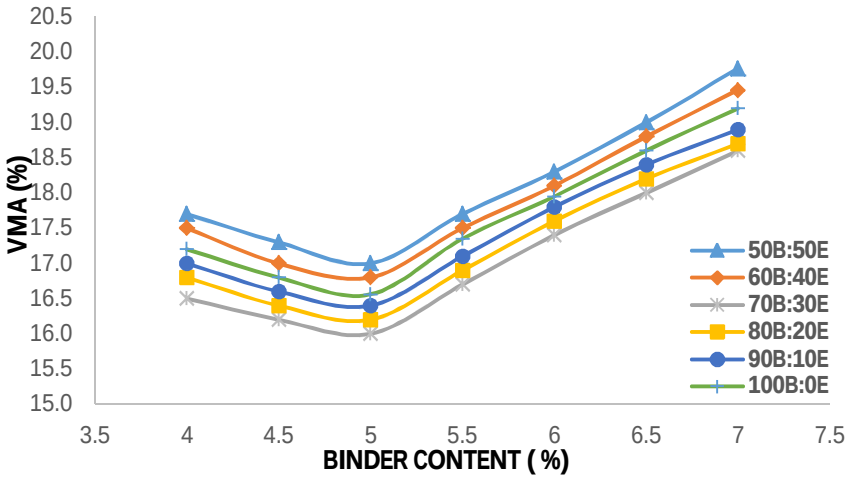

Fig. 4.42 Voids in mineral aggregates (VMA) vs binder content for mixes at 120°C

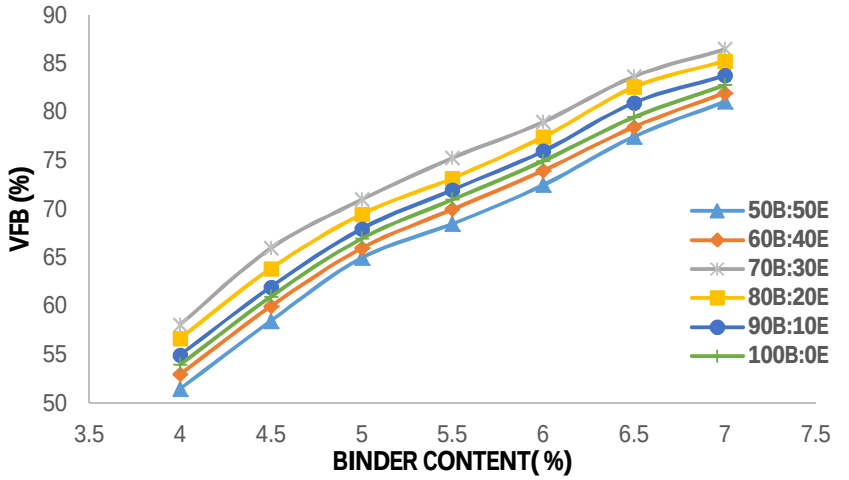

Fig. 4.43 Voids filled with bitumen (VFB) vs binder content for mixes at 120°C

4.4.2.3 Effect of different bitumen emulsion composition on Marshall Properties for warm BC samples prepared at 130^0C

Some important variations of Marshall Properties such as stability, unit weight, flow value, air voids, voids filled with mineral aggregate (VMA), voids filled with bitumen (VFB) for BC warm mixes prepared at 130^0C are shown in Figs 4.43 to 4.48.It is observed that the trends of variations for Marshall Properties with different binder content are similar to normal HMA. The stability, unit weight values increases to 5% binder content it shows highest stability and unit weight values for 80B:20E binder content then the value decreases

gradually. The flow value and air voids respectively increases and decreases with binder content. It is observed that first VMA decreases up to 5% binder content and then it increases at sharp rate with increase in bitumen concentration in mixes. Similarly VFB values of different binder content increase at sharp rate with increase in binder content. The OBC obtained is 5.1% for 80B:20E binder content.

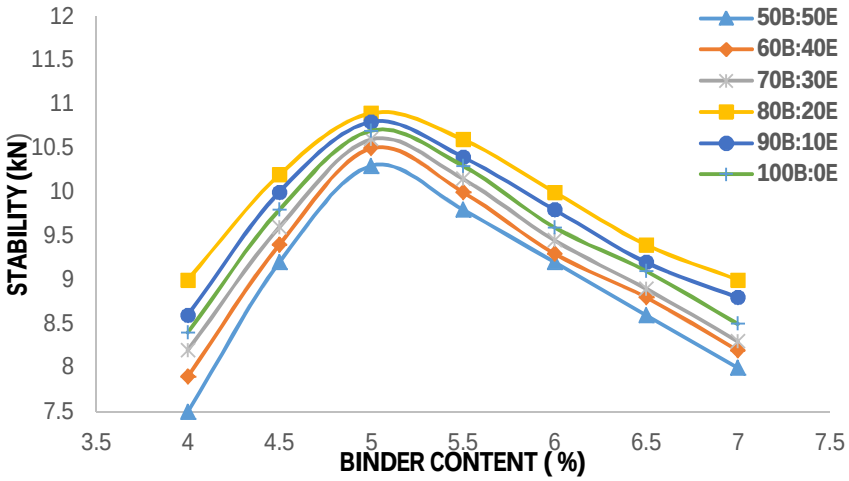

Fig. 4.44 Stability vs binder content for mixes prepared at 130°C

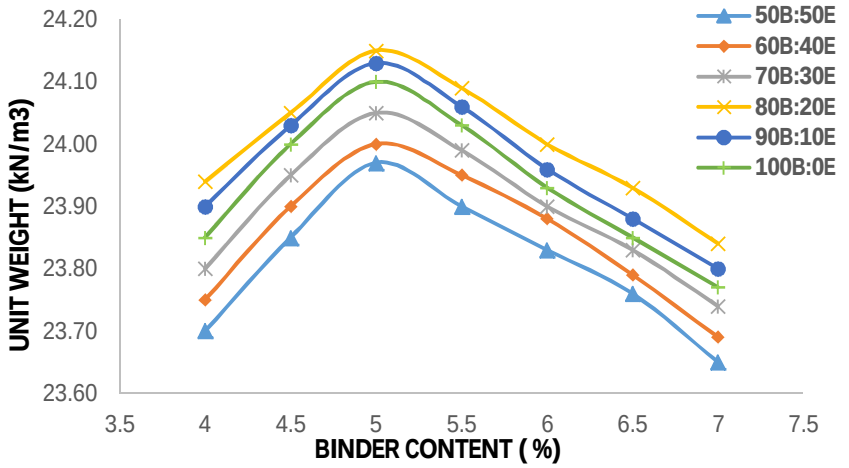

Fig. 4.45 Unit weight vs binder content for mixes prepared at130°C

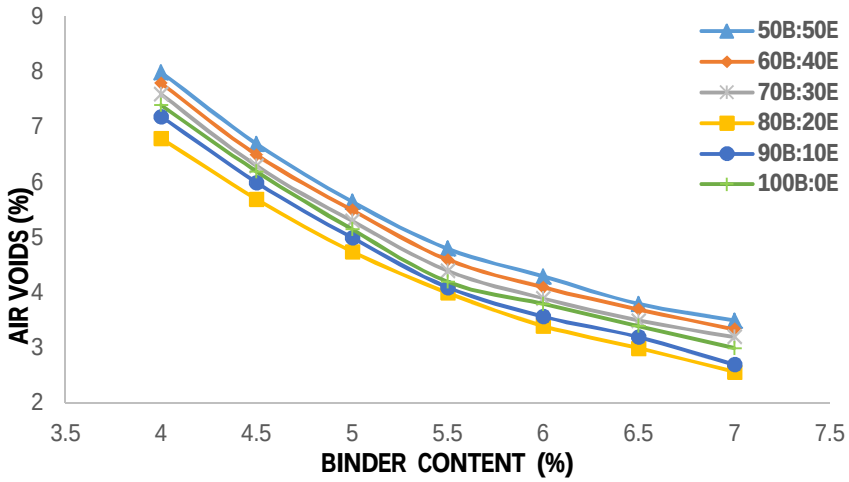

Fig. 4.46 Air voids vs binder content for mixes at 130°C

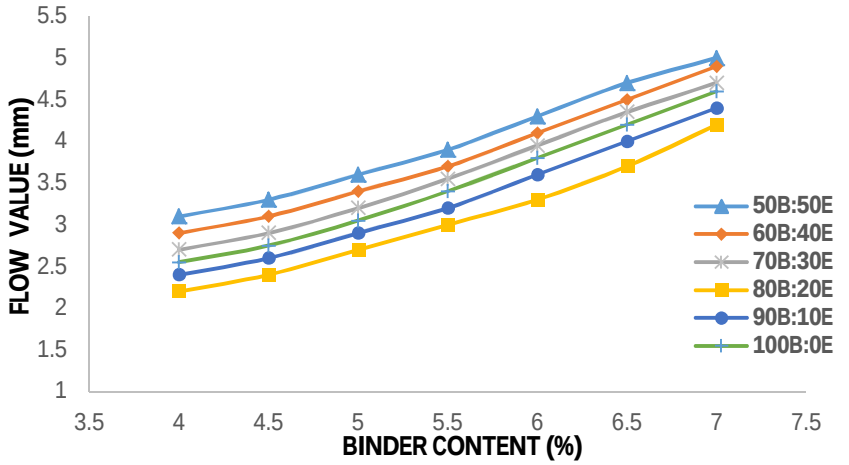

Fig. 4.47 Flow Value vs binder content for mixes at 130°C

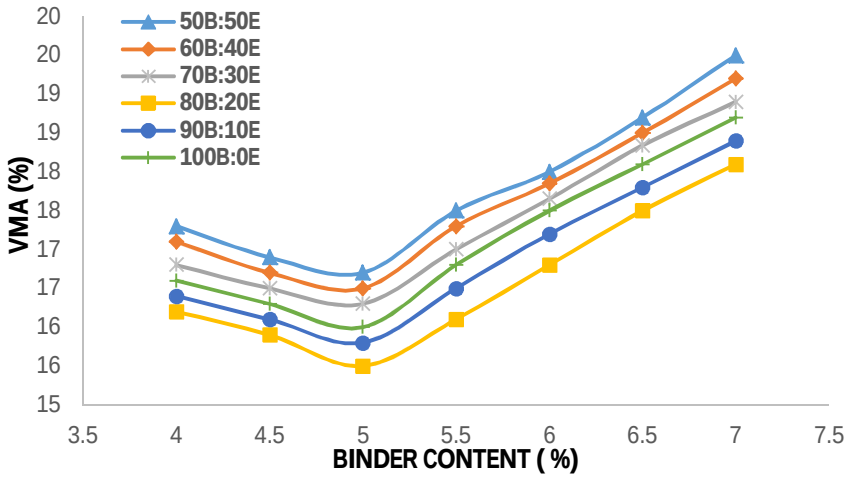

Fig. 4.48 Voids in mineral aggregates (VMA) vs binder content for mixes at 130°C

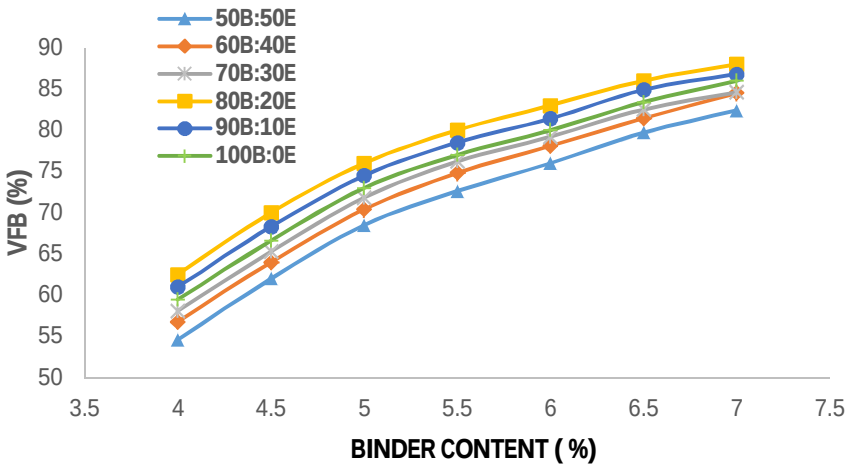

Fig. 4.49 Voids filled with bitumen (VFB) vs binder content for mixes at 130°C

Partial coating of aggregates with residual bitumen of bitumen emulsion, following by allowing emulsion to set and then mixing of partially coated aggregates with remaining bitumen at lower temperature than that used in conventional HMA. As shown in figures from 4.14 to 4.49, in general, the trends of Marshall Properties are in increasing order starting from 100%, followed by 90% and 80% and maximum at 70%, after which there is decrease with 60% and 50% bitumen. 70% refers to mix with 70% normal VG30 bitumen and 30% residual bitumen as derived from MS emulsion. The possible reason for this is as follows.

When the binder constitutes 100% bitumen and is used in the mix at a lower temperature than normally required, it has higher viscosity that is unable to properly coat all the aggregates in the mix causing extremely minimum engineering properties of the mix. The pre-coating provided by the emulsion is a benefit in this regard. However, it is observed that when less than 70% bitumen in binder is used, the properties start decreasing. This is due to the fact that with more emulsion, the pre-coated aggregates remain more bound and are too difficult to mix further with bitumen, causing gradual decrease in the properties.

The Optimum BC warm mix conditions are: mix temperature and OBC respectively 110°C 5% for 60B:40E, 120°C- 4.9% for 70B:30E and 130°C- 5.1% for 80B:20E binder contents.

4.4.3 Comparison of Marshall Properties of DBM and BC warm mixes prepared at Optimum Binder Content and composition

The optimum binder content for DBM and BC warm mixes at each temperature of 110°C, 120°C and130°C is obtained by taking average value of following three binder content found from above graphs i.e.

- Bitumen content correspond to maximum stability
- Bitumen content correspond to maximum unit weigh
- Bitumen content corresponding to the median of designed limits of percentage air voids in total mix

Table 4.1 Maximum Marshall Values for DBM and BC at their OBC

Mixing Temperature (°c)	Unit weight (kn/m^3)	Stability (kn)	Air voids (%)	Flow value (mm)	OBC (%)
DBM 110°C 70B:30E	24.06	11	4.6	2.5	5
DBM 120°C 80B:20E	24.25	11.8	3.08	2.4	5.1
DBM 130°C 90B:10E	24	10.5	4.08	2.6	5.4
BC 110°C 60B:40E	24	10.3	4.5	2.6	5
BC 120°C 70B:30E	24.16	11.5	4.4	2.4	4.9
BC 130°C 80B:20E	24.1	10.9	4.7	2.7	5.1

The test results as shown above are also presented in the form of a bar chart shown below in fig 4.50 and fig 4.51. It is seen that the DBM warm mix prepared at 120°C taking 80B:20E binder content shows better Marshall Properties having the highest stability and unit weight and less air voids as compared to samples with other mixing temperatures. Similarly for BC warm mix the mixes prepared at 120°C taking 70B:30E binder content shows better Marshall Properties.

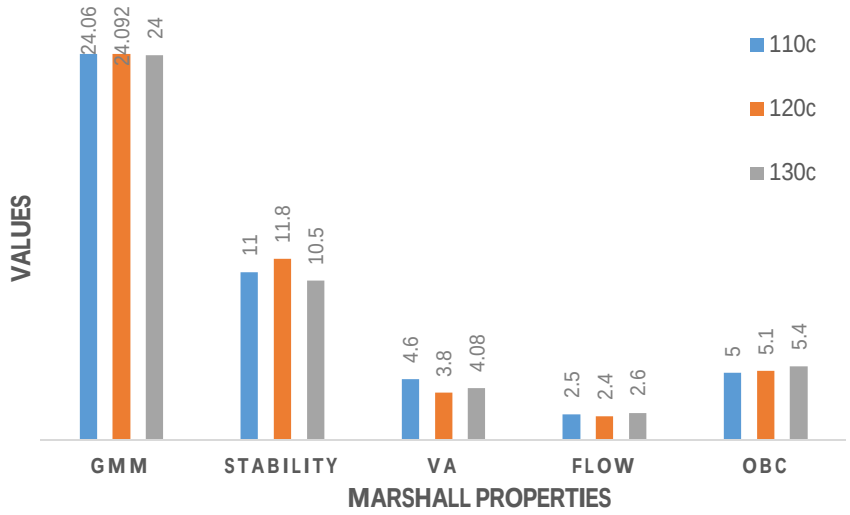

Fig.4.50 Bar chart for DBM warm mix showing Marshall Properties values at OBC

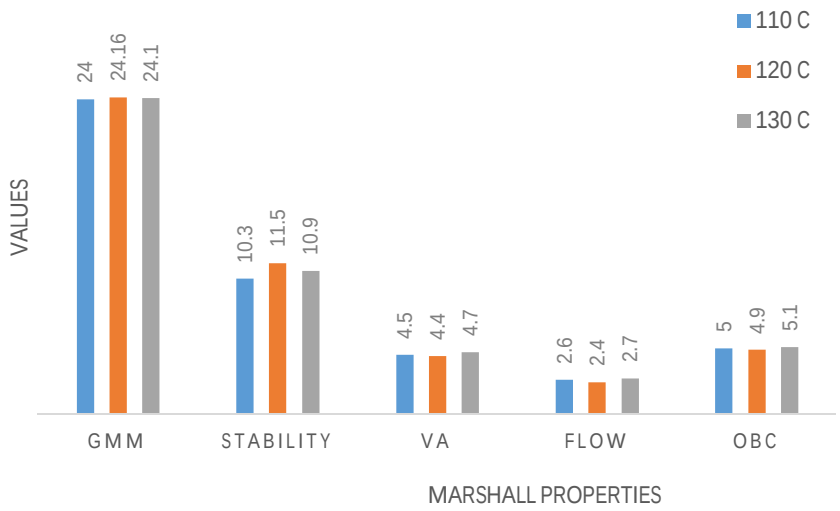

Fig.4.51 Bar graph for BC warm mix showing Marshall Properties values at OBC

4.5 Other Engineering Properties of Warm Mixes

4.5.1 Indirect Tensile Strength (ITS) for DBM and BC mixes at various mixing temperatures

Static indirect tensile test is used to determine the direct tensile strength (ITS) of the mix which helps to find out the resistance to thermal cracking. The static indirect tensile tests are carried out on DBM and BC mixes prepared at their optimum bitumen emulsion content at each mixing temperatures of 110°C, 120°C, 130°C.The effects of emulsion bitumen binder as well as temperature on both the mixes are studied.

Below Fig 4.52 and Fig 4.53 show the variations of indirect tensile strength with respect to temperature for both mixes of BC and DBM. It is seen that the ITS value decreases with increase in temperature. The BC warm mix prepared at 120°C by taking its 70B:30E as optimum emulsion binder content shows higher ITS value followed by mixes prepared at 110°C and 130°C. Similarly DBM mix prepared at 80B:20E binder content shows higher ITS value as compared to other DBM warm mixes. The ITS value of BC and DBM HMA mixes shows highest ITS values as compared to its respective wma mixes.

The samples prepared at temperature of 120°C for both the mixes by taking its optimum bitumen-emulsion composition gives higher ITS values for compared to other mixing temperatures.

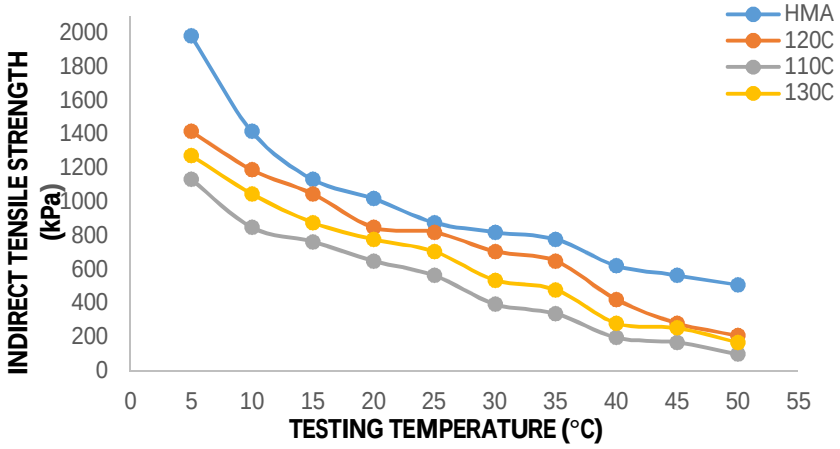

Fig 4.52 Indirect Tensile Strength for BC mixes at various mixing temperatures

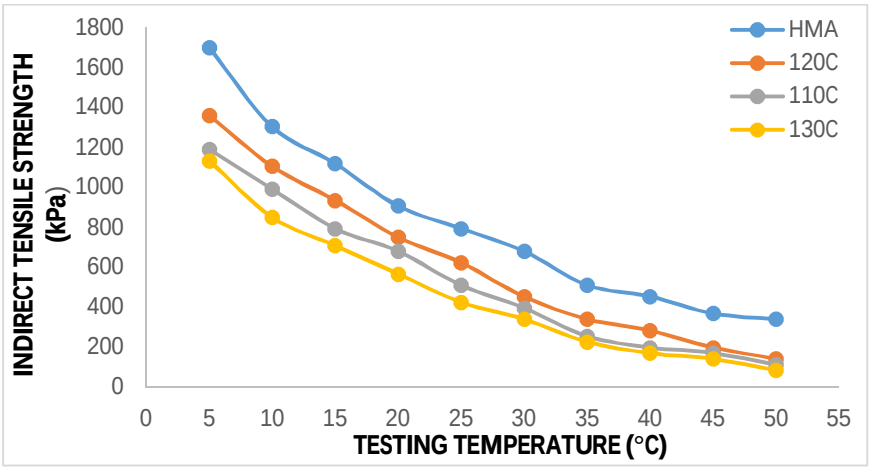

Fig.4.53 Indirect Tensile Strength for DBM mixes at various mixing temperatures.

4.5.2 Tensile Strength Ratio of DBM and BC mixes

Tensile strength ratio is used to indicate the resistance to moisture induced damages to a paving mix. Below table 4.2 shows the Tensile strength ratio of DBM and BC mixes. This has been calculated for BC and DBM warm mixes at various mixing temperatures by considering optimum binder content of each mix type. The tensile strength ratio of BC mix prepared at 120°C taking 70B:30E emulsion binder content shows higher TSR value as compared to other mixing temperatures of BC. Similarly DBM mix prepared at 120°C taking optimum binder content of 80B:20E shows higher TSR value as compared with other DBM warm mixes. TSR value of both BC, DBM HMA shows higher TSR values as compared. The viscosity of bitumen is the measure of its resistance to flow which affects the workability and resistance to deformation of mixture. In this study bitumen is used in two stages. While emulsion is used in initial stage, bitumen at elevated temperature is used in the last stage. Increase in temperature is normally desirable for a bituminous mix. At a higher temperature of 130°C it is observed that the residual bitumen involved in pre-coating tends to flow and interact with the additional conventional bitumen. However, the resulting flowing binder has no required viscosity to give the necessary coating to each aggregate particle and hence resulting mixes give inferior engineering properties of the warm mixes.

Table 4.2 Tensile strength ratio values of different mixes

Tensile Strength Ratio of DBM mixes at various mixing temperatures		
HMA	83 %	Minimum 80% (as per MORTH Table 500-17)
110 °C	78.8 %	
120 °C	80%	
130 °C	78.3%	
Tensile Strength Ratio of BC mixes at various mixing temperatures		
HMA	83.6%	Minimum 80% (as per MORTH Table 500-17)
110°C	78%	
120°C	80.7%	
130°C	79%	

4.5.3 Retained Stability for DBM and BC mixes

Another way of assessing the moisture induced damage to a paving mix is by determining the retained stability of the concerned mix. This has been calculated for both DBM and BC mixes at mixing temperatures of 110°C, 120°C, 130°C at their respective optimum binder contents. The results of this study are presented in Table 4.3. It is seen that the retained stability of DBM shows better results as compared to BC mixes. DBM and BC warm mixes prepared at 120°C taking Optimum Emulsion Binder of 80B:20E and 70B:30E respectively shows higher retained stability values.

Table 4.3 Retained Stability for DBM and BC mixes at various mixing temperatures

Types of mix with temperature	Avg. stability after half an hour in water at 60 °c (kN)	Avg. stability after 24 hours in water at 60 °c (kN)	Avg. retained Stability, in %	Design requirement
DBM HMA	13	10.3	79	Minimum 75% (as per MORTH Table 500-17)
DBM 110 °C	11	7.8	70.9	
DBM 120 °C	11.8	9	76.27	
DBM 130 °C	10.5	7.1	67.61	
BC HMA	14.4	11.5	79.86	
BC 110 °C	10.3	7	67.96	
BC120 °C	11.5	8.8	75.52	
BC130° C	10.9	7.8	71.55	

4.6 Concluding remarks

The laboratory study on warm mixes prepared on DBM and BC aggregate gradation at three different mixing temperature of 110°C, 120°C, and 130°C using medium setting emulsion (MS) and VG30 binder in various Binder Emulsion ratio of 50B:50E, 60B:40E, 70B:30E, 80B:20E, 90B:10E, 100B:0E and cement as filler. DBM and BC mixes prepared using three different mixing temperatures and six different Emulsion Binder proportion for each mixing temperature finally evaluates, that DBM and BC warm mixes prepared at 120°C using 80B:20E and 70B:30E Binder Emulsion proportion shows better Marshall properties as compared to other DBM and BC warm mixes prepared using other binder emulsion contents and mixing temperatures. The Indirect Tensile Strength Test (ITS), Tensile Strength Ratio (TSR), and Retained Stability results of DBM, BC warm mixes prepared at 120°C using 80B:20E, 70B:30E shows better results as compared to other warm mixes of both gradations.

Hence for the preparation of warm mixes of DBM and BC 120°C temperature and bitumen-emulsion composition of 80B:20E, 70B:30E respectively can be considered for better warm mix design.

4.6.1 Comparison of DBM and BC warm mix at 120 °C with normal HMA

The overall study of the research work reveals that warm mixes of DBM and BC using 80B:20E, 70B:30E binder emulsion content respectively at 120°C shows better Marshall Properties in terms of stability, Unit weight, Air Voids. Hence warm mixes of DBM and BC prepared at 120°C is compared with normal HMA of both the mixes for Marshall Properties comparative study .The graphs shows comparison of DBM and BC warm mixes prepared at 120°C using bitumen Emulsion content of 80B:20E and 70B:30E respectively with normal HMA. Marshall Properties like Stability, Unit Weight, Air Void, Flow values of both DBM and BC warm mixes are compared with normal HMA.

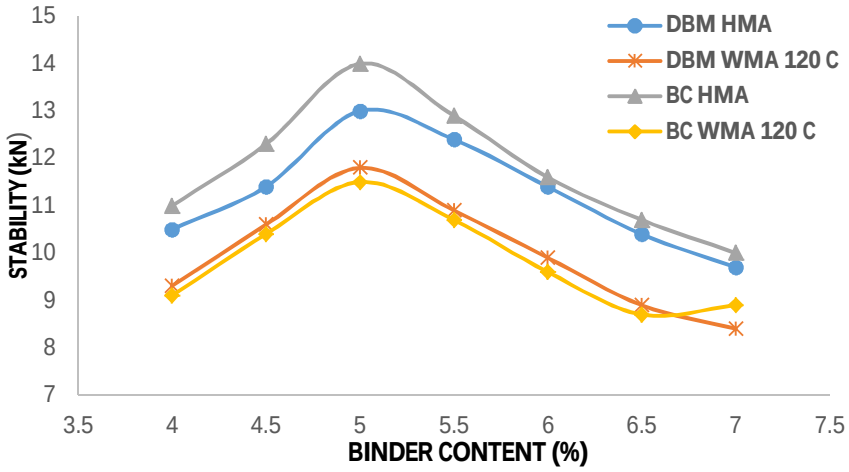

Fig4.54 Stability vs binder content of HMA and WMA mixes

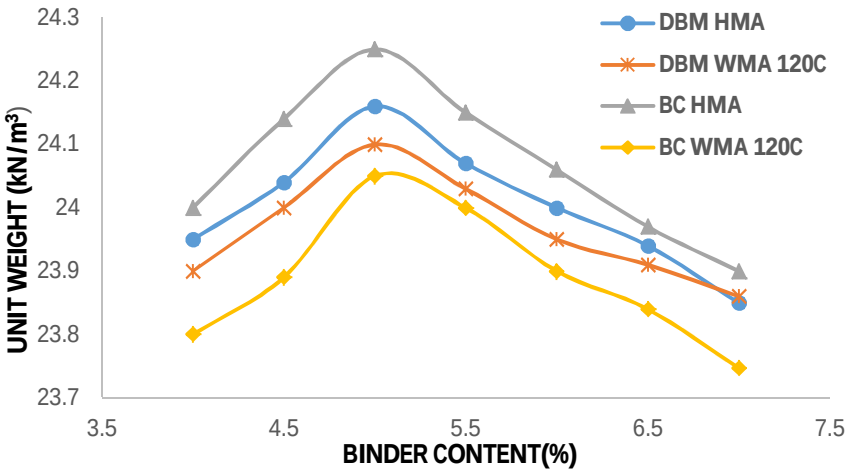

Fig. 4.55 Unit Weight vs binder content for HMA and WMA mixes

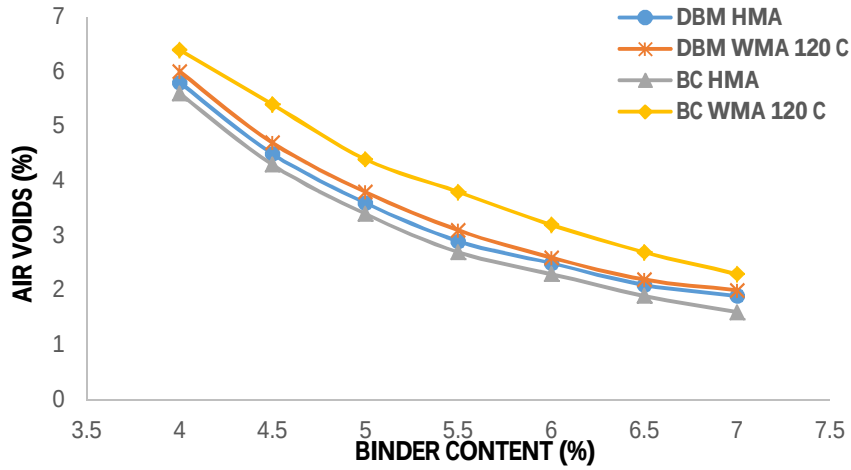

Fig 4.56 Air Void vs binder content for HMA and WMA mixes

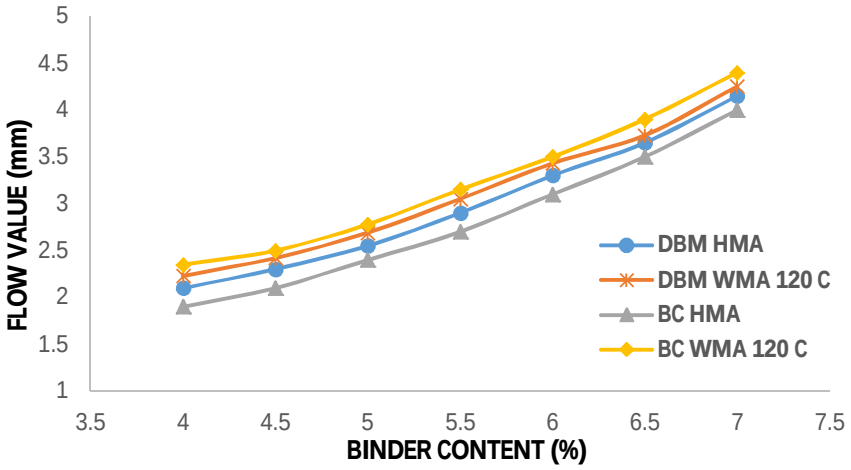

Fig 4.57 Flow Value vs binder content for HMA and WMA mixes

Chapter 5

CONCLUSIONS

5.1 Introduction

In this study, an attempt has been made to prepare warm mixes with medium setting (MS) emulsion as initial coating of stone chips followed by application of conventional VG 30 bitumen. As a result of extensive laboratory tests conducted on Marshall warm mix specimens with DBM and BC gradation to study various parameters, the following conclusions are drawn.

5.2 DBM Mixes

Based on Marshall Properties of mixes with DBM gradation, the optimum setting time of emulsion and type of filler were found to be 9 hours and cement respectively. These parameters have been considered in subsequent studies.

- Based on Marshall Tests, for warm mixes prepared at 110°C for DBM warm mixes optimum binder composition i.e. bitumen emulsion ratio in binder is found to be 70:30 and optimum binder content is observed to be 5%. Similarly for mixes prepared at 120°C and 130°C, for DBM warm mixes the optimum binder content and optimum binder composition are found to be 5.1%, 80:20; and 5.5%, 90:10 respectively.
- Satisfactory Marshall Characteristics are observed for mixes prepared at all three temperatures at their optimum binder contents and binder compositions.
- The maximum indirect tensile strength value is observed for warm mixes prepared at 120^0C.
- The tensile strength ratio and retained stability values for DBM warm mix at 120 °C is observed to be higher as compared to other DBM warm mixes prepared at 110°C, 130°C.
- Out of the three temperatures tried in this study, it is observed that the mixes prepared at 120^0C for DBM warm mix offer highest stability and indirect tensile values

satisfying other Marshall parameters. Hence the specific mix i.e. mix prepared at 5.1% binder content and 80:20 bitumen emulsion composition considered to be the most suitable warm mix which is normally comparable with normal HMA.

5.3 BC Mixes

Based on Marshall Properties of mixes with BC gradation, the optimum setting time of emulsion and type of filler were found to be 9 hours and cement respectively. These parameters have been considered in subsequent studies.

- Based on Marshall Tests, for warm mixes prepared at 110°C for BC warm mixes optimum binder composition i.e. bitumen emulsion ratio in binder is found to be 60:40 and optimum binder content is observed to be 5%. Similarly for mixes prepared at 120°C and 130°C,for BC warm mixes the optimum binder content and optimum binder composition are found to be 4.9%, 70:30; and 5.1%, 80:20 respectively.
- Satisfactory Marshall Characteristics are observed for mixes prepared at all three temperatures at their optimum binder contents and binder compositions.
- The maximum indirect tensile strength value is observed for warm mixes prepared at 120^0C.
- The Tensile Strength Ratio and Retained Stability value for BC warm mix at 120°C is observed to be higher as compared to other BC warm mixes prepared at 110°C, 130°C.
- Out of the three temperatures tried in this study, it is observed that the mixes prepared at 120^0C for BC warm mixes offer highest stability and indirect tensile values satisfying other Marshall parameters. Hence the specific mix i.e. mix prepared at 4.9% binder content and 70:30 bitumen emulsion composition considered to be the most suitable warm mix which is normally comparable with normal HMA.

Hence it can be concluded in general that for preparation of bituminous emulsion based warm mixes of DBM and BC gradation the optimum temperature for the preparation in both types of mixes is 120°C. The optimum bitumen-emulsion composition for warm mixes with DBM and BC gradations are found to be 80:20 and 70:30 respectively.

5.4 Future scope of works

1. Many properties of BC and DBM mixes such as Marshall Properties, static tensile strength, tensile strength ratio, retained stability have been studied in this investigation by using VG 30 penetration grade bitumen and medium setting emulsion (MS). However, some of the properties such as fatigue properties, resistance to rutting, dynamic indirect tensile strength characteristics and dynamic creep behaviour needed to be investigated.
2. In present Study Medium Setting Emulsion and VG 30 binder have been used. The research can further be enhanced by varying proportions of the Emulsion Bitumen content.
3. Variation of temperatures can be considered for the warm mix preparation so lower temperatures can also be studied for mix preparation.
4. Various other types of aggregate grading, Filler, Binder, Emulsion and Additive can be considered for further studies.

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